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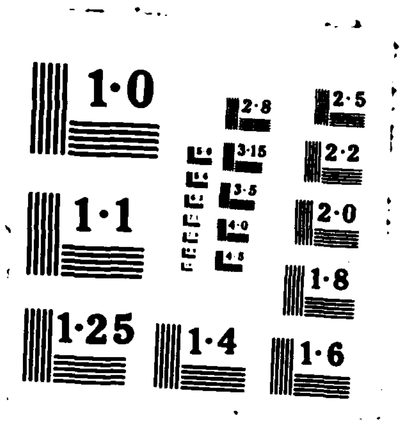
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MATERIAL PROPERTIES TEST 2 (MP-2) REVIEW AND FINAL DATA ANALYSIS

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Final Report

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In 1983, three spherical buried high explosive charges (9.8 kg, 116 kg, and 20 T) were fired to obtain dynamic material properties for in situ dry alluvium. This report contains a concise summary describing the test series objectives, rationale for gaging and placement, overall analysis, and recommendations for future tests. The key question concerning the design was what type of test should be fielded to give the most information about material properties used in calculating nuclear surface bursts. Particular requirements for measurement validation and redundancy of data were also key factors in the design. Several alternate approaches to data analysis by the various participants yielded results that pointed out the ability to determine uniaxially loading parameters of the material; however, stress difference and unloading estimates are still elusive. Important results, described in some detail, are the estimation of the dynamic loading uniaxial strain versus stress relationship, approach to development of a material properties test, analysis of stress gage performance, and recommendations for future material properties testing.

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SUMMARY

In 1983 three spherical buried high explosive charges (9.8 kg, 116 kg and 20 T) were fired to obtain dynamic material properties for in situ Yuma Test Site, dry alluvium. Much has been written concerning the Material Properties (MP) Series; however, no concise summary describing test objectives, rationale for gaging and gage placement, overall analysis of the test data, or recommendations resulted. This report presents that summary.

The main event of the Material Properties Series, MP2, was 20 T of nitromethane contained in a buried fiberglass and wood sphere at a depth of 20 m below the surface. The original plan consisted of a preliminary calibration shot (MP1) of 9.8 kg C-4 explosive buried at precisely the same location as MP2. However, the smallness of MP1 did not adequately address cable and gage survivability issues, so an additional HE test was fielded. This was MP3, 112.6 kg of TNT buried at a depth of 5 m. Since only survivability issues were addressed, the dry alluvium test site at McCormick Ranch, New Mexico, was used for this test. MP1 (Ref. 1) and MP3 (Ref. 2) results were for calibrating MP2 and have little influence with the main test's objectives and theoretical design. Results and details are not discussed further.

This report deals with primarily three major areas. Firstly, the design objectives and philosophy are discussed in detail. The key question concerning the design was what type of test should be fielded to give the most information about material properties used in calculating nuclear surface bursts. Certainly there is an abundance of test types; however, particular requirements for measurement validation and redundancy of data were factored into the design. Secondly, the roles, objectives and results from the participants are discussed. Each participant had separate objectives for analysis and their results lead to differing conclusions concerning the value of the

test. Finally, general results from the test are considered, and an analysis of the key resulting uncertainty, namely gage validation, is presented. This report should not be considered a record of fielding or routine data presentation (for this see Ref. 3), but is a report of the philosophy that led to the fielded design and resulting analysis.

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INTRODUCTION

Conventional wisdom (Refs. 4 and 5) suggests that the only method to accurately assess true material properties at a particular site of interest is through in situ field testing. Prior to field testing for material properties, generally the site is sampled with borehole drilling techniques that provide samples for measuring physical properties (e.g., bulk and grain density, air-filled voids, seismic velocities) and "nondisturbed" samples for testing. The samples are then tested in the laboratory to obtain various stress-strain relationships. On the one hand, it has been shown (Ref. 5) that the samples are disturbed (e.g., by alteration of the delicate cementation, removing regional and lithostatic stresses) and provide only specific estimates for small samples. Because of the disturbances, in situ testing is thought to be required to provide material estimates that do not contain uncertainties resulting from sampling and placing the sample in the laboratory environment. Additionally, the stress and strain paths followed in the lab may not fully replicate those produced in the field testing. On the other hand, field tests also have difficulties associated with them. The test has to be fielded, immediately altering the in situ conditions somewhat. There are uncertainties in instrumenting the field test (gage survival, uncertainties and validation). There is no direct measure of stresses and strains, so the constitutive relationships must be interpreted with the data. There are limits of stress above which field data cannot be obtained but at which laboratory tests can. A final use of an in situ test is calibration of the site for more precise empirical estimates.

A myriad of in situ tests can be fielded at any particular site. These range from complicated nuclear simulations or HE cratering shots to a simple planar slab of explosives designed to give uniaxial stress versus strain paths. This series was a first attempt to completely analyze a spherical charge buried in dry alluvium. Because it was a first try, many resources were put into this test, more than are probably necessary for a true, simple material properties test. A spherical test was basically chosen because of the strain paths produced and because the release of stress was not perturbed by edge effects of the driver as occurs in planar and cylindrical tests (Ref. 4).

Because of the interest in strain paths and release paths, more was being asked from the instrumentation than in the past. Generally, in the past, arrival times, rise times, and peak velocities were considered sufficient to define a loading curve. In this series much interest was placed in the decay from peak stress and velocity. Because of the very low accelerations postpeak, and the previously documented nonzero baseline shifts in stress measurements, instrumentation was being driven to perhaps excessive limits.

The original test objectives were quite simple. "The MP2 test event was designed to provide the baseline material properties at the test site for input into the design and analysis of the CARES-Dry Main Event" (Ref. 3). In addition to this rather straightforward objective, four additional objectives were considered:

a. Are in situ tests really required, considering the improved laboratory tests?

b. What are the measured strain paths for a spherical test?

c. Are strain rate effects apparent in alluvium, and are these effects important to calculations?

d. What type of analysis should be done with in situ field test data?

SITE CHARACTERISTICS

For any material properties test to be successful, a complete characterization of the site must be done. The recommended procedure leading up to the main MP2 event is outlined in Reference 4. This includes rather simple site characterization, including site visits, seismic refraction surveys to identify important physical boundaries and properties, borehole drilling, sampling and logging, and, finally, laboratory testing.

Details of the site are contained in Reference 1. A map of the test site is seen in Figure 1. Basically, the site is typical dry alluvium with both bedrock and water table sufficiently deep so as not to have any influence on this test. Simple lab tests of the material provided physical properties of the material. The soils are predominantly low to nonplastic, slightly to moderately cemented, well-graded, fine to coarse grained, silty sands with occasional decomposed (weak) granite nodules. The material is most likely Haloane sheetwash/stream bed sands and gravels with fine aeolian sands and silts. The sheetwash deposition leads to numerous thin bedding layers. These beds, initially found during drilling, separate zones that are well cemented from zones containing uncemented coarse sands. This particular material differs from other generic dry sites because of the 15-20 percent of fines (- #200 fraction) that are clays. The clays, observed in core samples, are of both kaolinite and montmorillonite. Figure 2 (from Ref. 6) presents basic physical data from the test site for water content, dry and bulk density, and calculated air voids.

Many mechanical property tests were done on the "undisturbed" core samples obtained in the field. A brief description follows (Ref. 6).

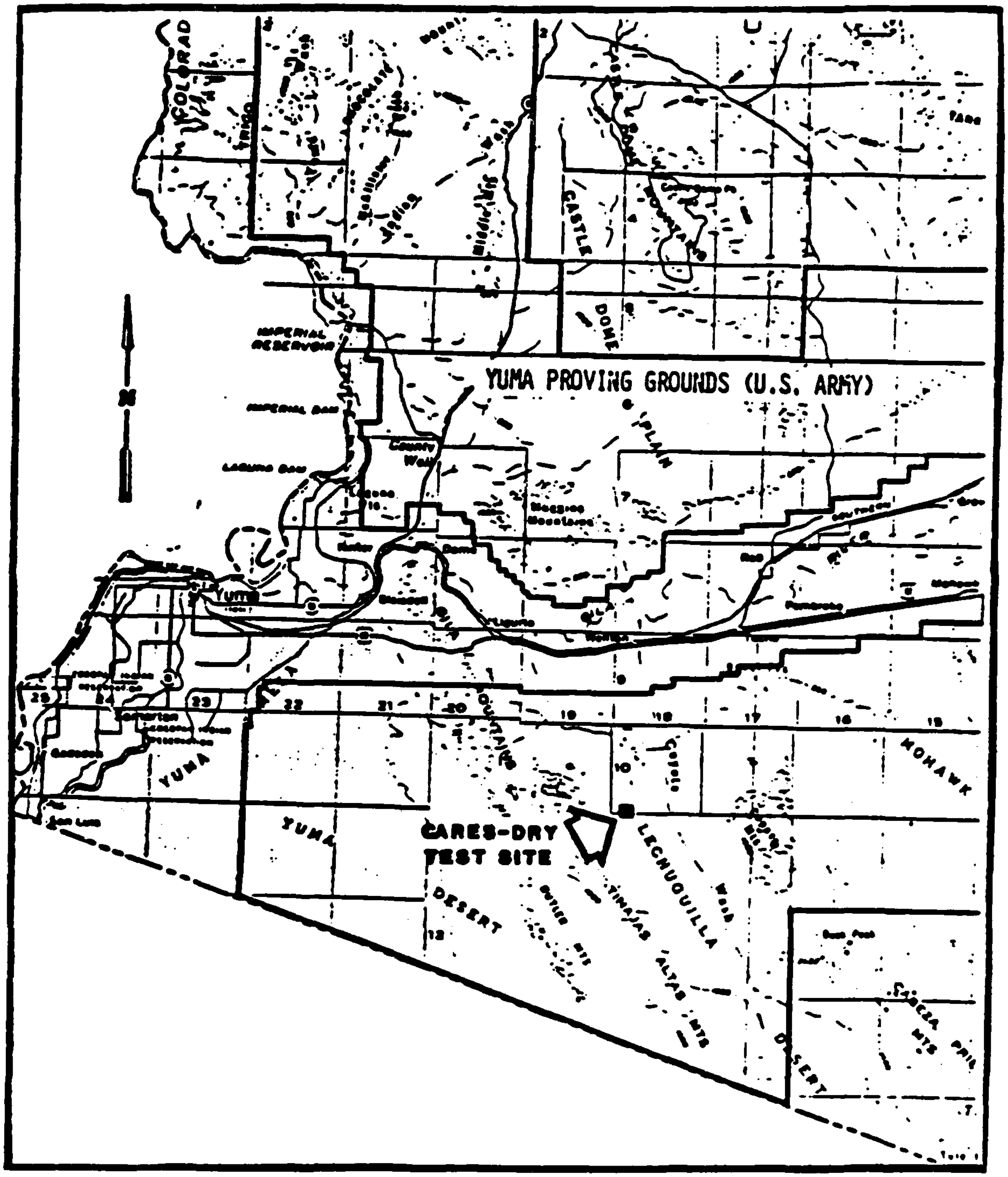


Figure 1a. Test area location

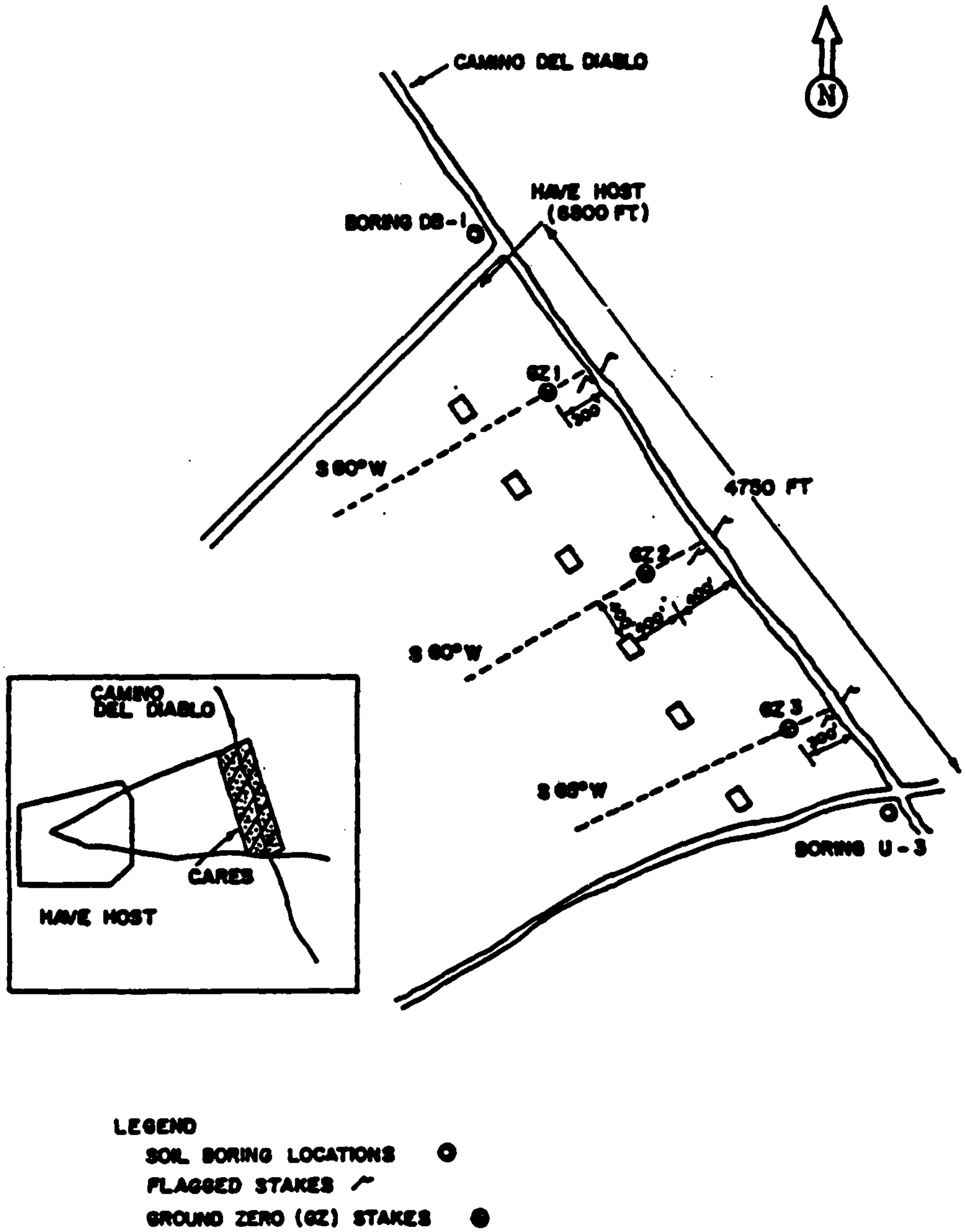


Figure 1b. Test-bed location (GZ 3)

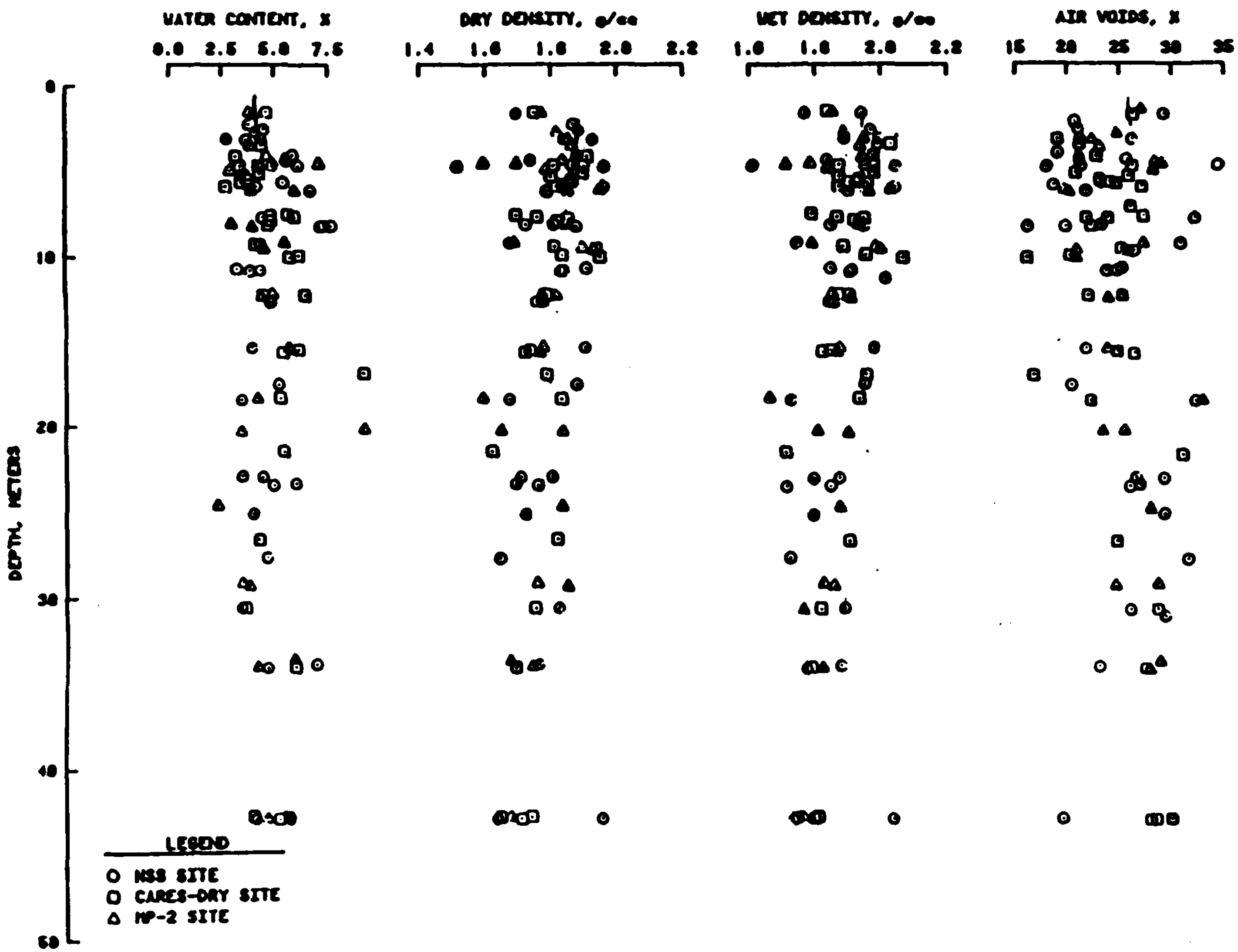


Figure 2. Composition data obtained for undisturbed specimens used for mechanical property tests

a. Two types of uniaxial strain (UX) tests were conducted:

   (1) The first (designated UX) is conducted by applying an axial (vertical) pressure to a wafer-shaped specimen that is physically constrained from deflecting radially. Measurements are made of the applied axial stress and the specimen's height change. The data are plotted as axial (vertical) stress versus axial (vertical) strain, the slope of which is the constrained modulus M. Loading is on the order of a few milliseconds.

   (2) The second type of UX test (designated K_o) is conducted by applying radial pressure to a specimen until a slight inward movement of the diameter is detected. Axial load is then applied until the specimen returns to its original radial position (zero radial strain). This process is repeated throughout the test. As in the UX test, the data are plotted as axial stress versus axial strain, the slope of which is the constrained modulus M. When the data are plotted as principal stress difference versus mean normal stress, the slope, assuming elastic theory, is 2G/K, or in terms of Poisson's ratio ν, $3(1 - 2\nu)/(1 + \nu)$. This is basically a static test.

b. The isotropic compression (IC) test subjects a cylindrically shaped specimen to an equal all-around confining pressure while measurements of the specimen's height and diameter changes are made. The data are normally plotted as pressure versus volumetric strain, the slope of which is the bulk modulus K.

c. The triaxial compression (TXC) test is conducted after a desired confining pressure is applied during an IC test.

While the confining pressure is held constant, axial load is increased and measurements of the specimen's height and diameter changes are made. The data can be plotted as principal stress difference versus axial strain, the slope of which is Young's modulus E, or as principal stress difference versus principal strain difference, the slope of which is twice the shear modulus G. The maximum principal stress difference the specimen can support or the principal stress difference at 15 percent axial strain during shear loading (whichever occurs first) is defined as the "peak" strength.

d. The triaxial extension (TXE) test is also conducted after a desired confining pressure is applied during an IC test. The TXE test chamber is different from the TXC chamber in that the axial piston is the same diameter as the specimen. While lateral pressure is held constant, vertical pressure is decreased and measurements of the specimen's height and diameter changes are made. As with the TXC test, the data are plotted as principal stress difference versus axial strain or as principal stress difference versus principal strain difference. The maximum negative principal stress difference or the point at which the material separates (whichever occurs first) is defined as the "peak" (negative) strength.

Initial laboratory uniaxial strain versus stress curves were presented from the laboratory tests (Figs. 3a and 3b) (Ref. 7). As suggested by Reference 5, these were modified to a "best estimate" for in situ properties for the site (Fig.4).

Nothing particularly unusual went into defining these geomechanical properties for the test site and they serve as a starting point for future testing. They do represent a complete set of properties obtainable from a standard laboratory suite.

Preliminary Material Properties for ISST: Best Estimate High-Pressure Uniaxial Strain Compressibility Relations For Millisecond-Type Loadings on Cemented Sand Layers 1-3

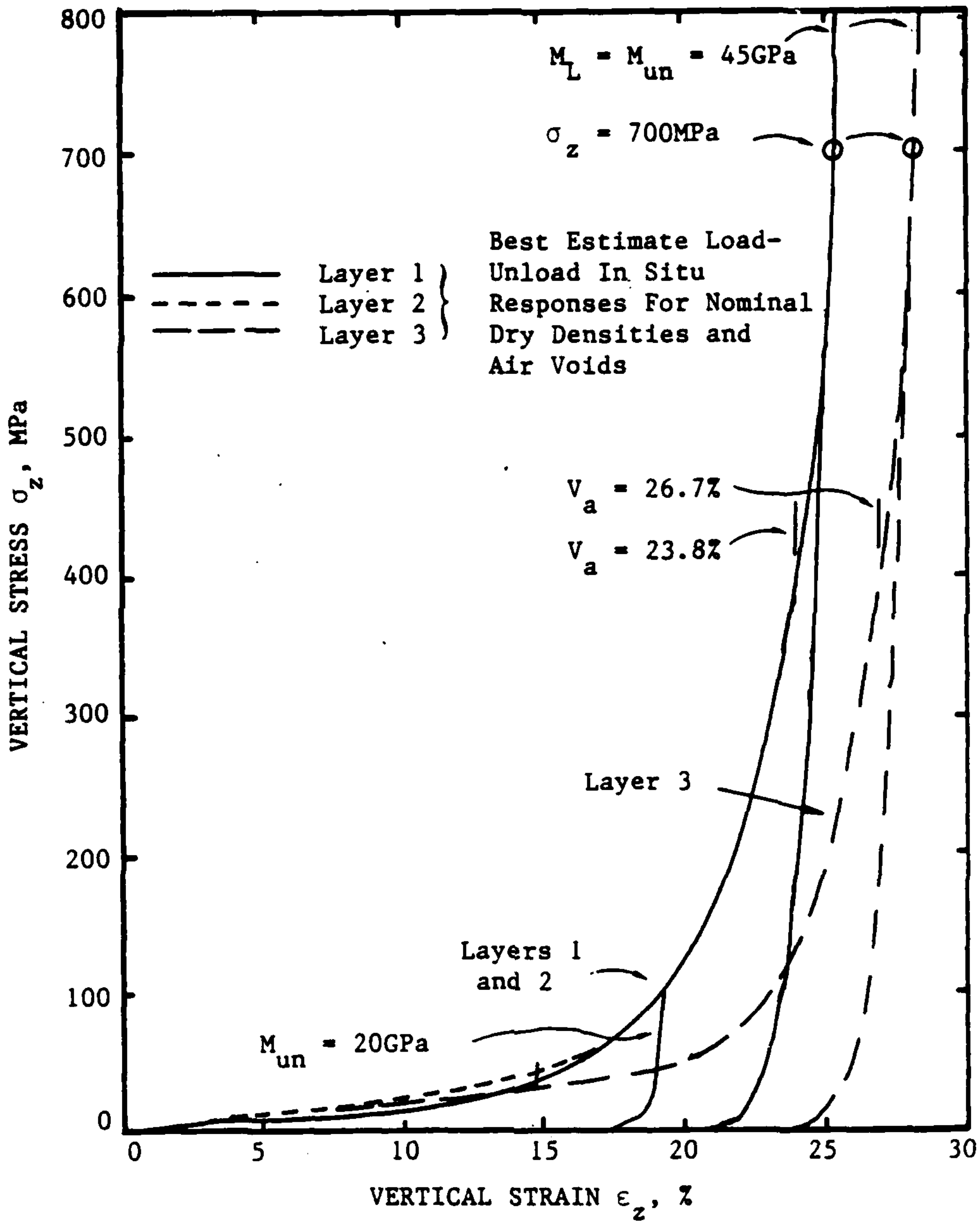


Figure 3a. Representative uniaxial stress-strain curves to 800 MPa for the top three layers at the MP2 site (from Ref. 7)

Preliminary Material Properties for ISST: Best Estimate High-Pressure Dynamic UX Stress Path Responses and Strength Envelope for Millisecond-Type Loadings on Cemented Sand Layer 3

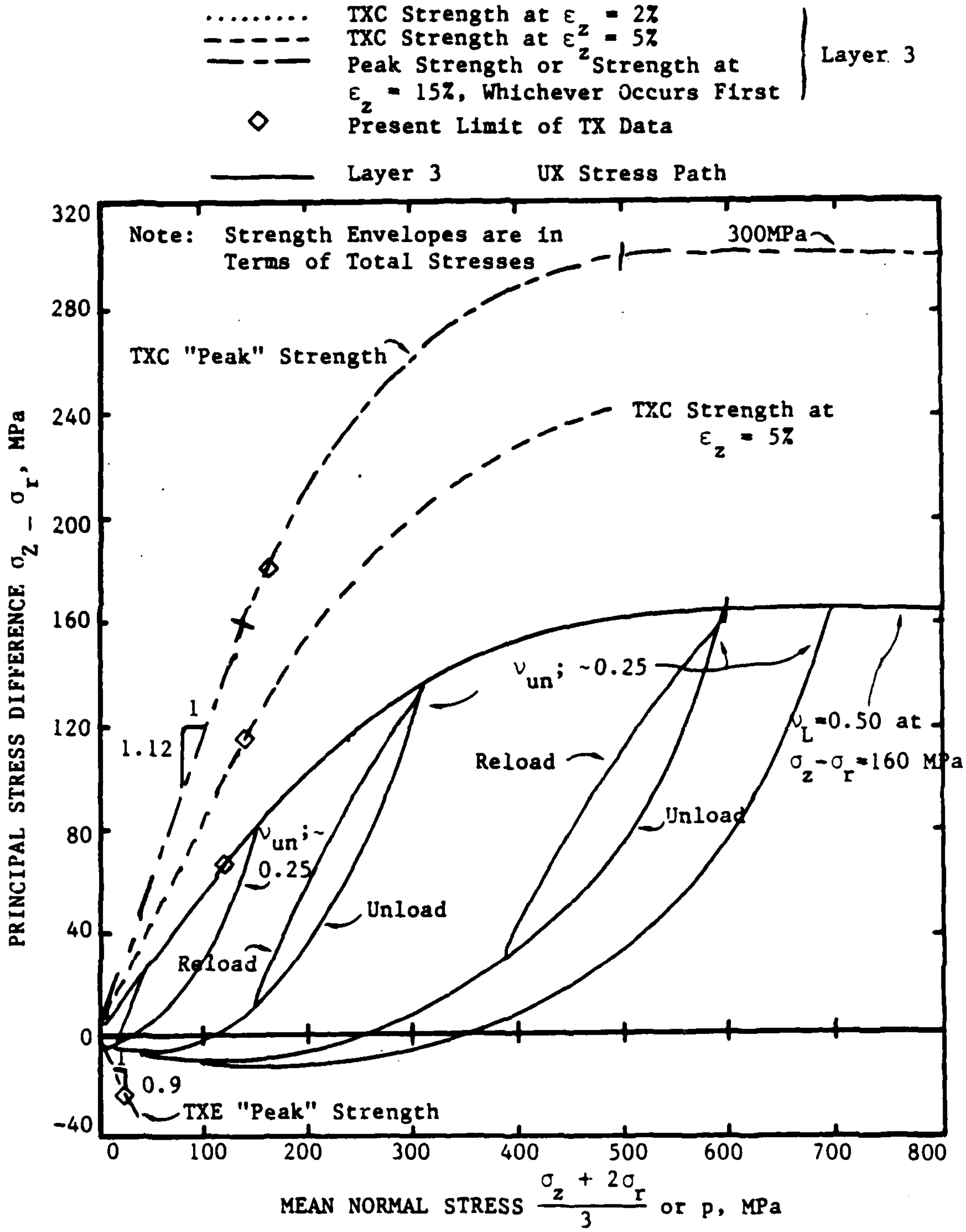


Figure 3b. Stress difference paths and yield strengths for layer 3 of the MP2 site (from Ref. 7)

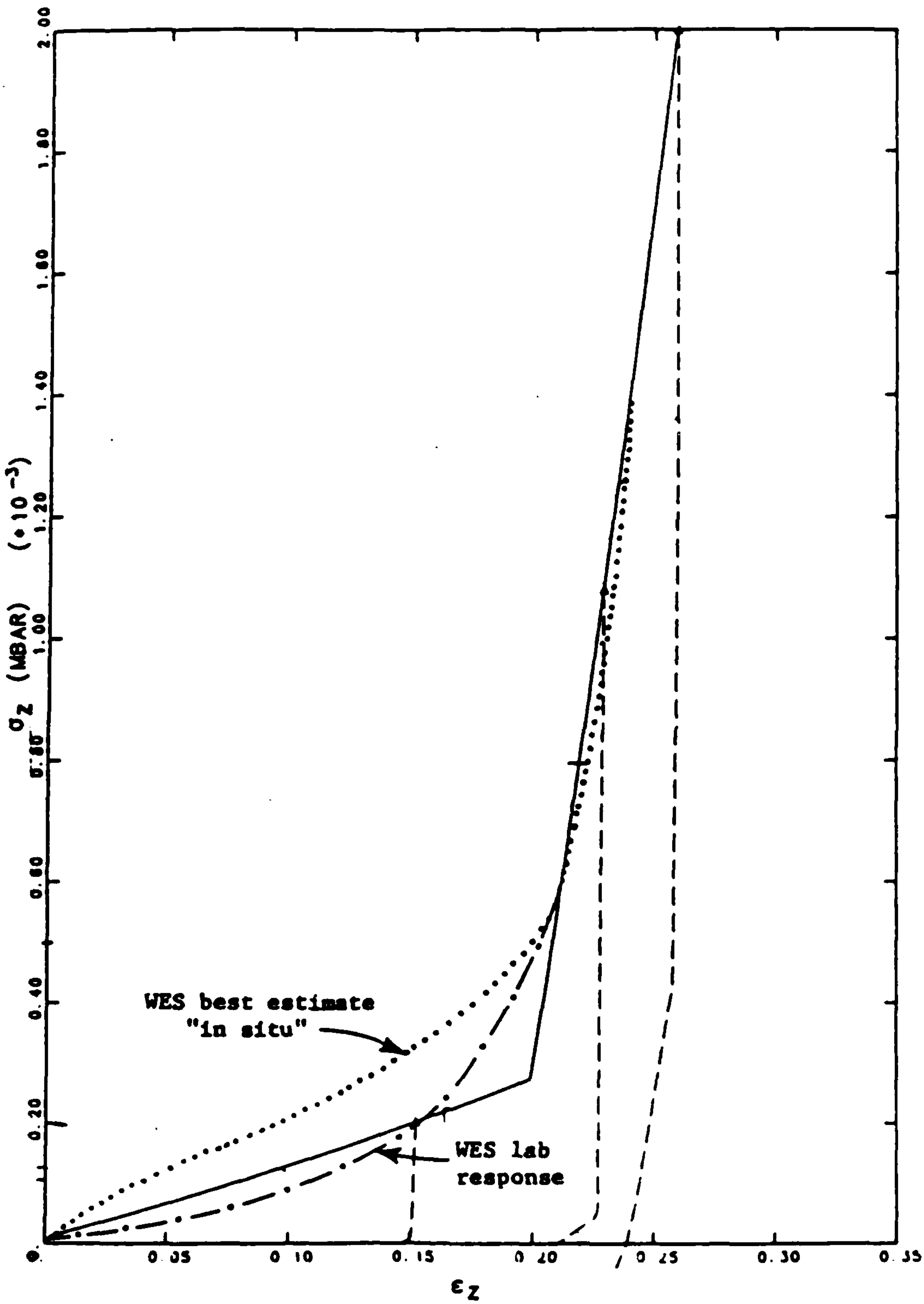


Figure 4. Comparison of the CRT "halfway" model fit and the WES representative uniaxial load-unload curves for layer 3 of the MP2 site

In addition, they represent what can be done at a test site for a cost of 20% of the next stage, namely, in situ testing. A major question posed is, are they sufficient for calculating accurate soil response, or is an in situ test required? This, then, becomes an objective for some of the participants.

TEST DESCRIPTION

Even though very precise data and error bounds were obtained from the laboratory tests, they still represented data for disturbed (both physically and removed from regional stress fields) samples. Also, the samples are for specific cores, or points, and are not total averages of in situ properties. The "best in situ estimate" was estimated by methods proposed in Reference 5 and could only be validated through field testing.

CHOOSING A SPHERICAL TEST

In order to confirm that the laboratory estimates have been properly interpreted and used, one test at the site using one of the several in situ, high explosive testing techniques was required. These tests will subject the material to more realistic loading environments than the previous methods. In addition, the question of soil disturbance due to sampling for laboratory analysis does not come into play and the global site will be sampled as an entity. There are limitations to the in situ field testing in that the data obtained is not in terms of stress versus strain as it is in the laboratory. Rather, velocity-time histories and stress-time histories are measured at specific points in the free field. These point measurements must be related to constitutive models for the whole site. The major problems associated with the field tests are how does one validate the free field measurements and how does one relate the measurements to the constitutive model required for the predictions?

In order to directly calculate the state of the material, the entire stress and strain fields must be determined. Although not impossible, the required instrumentation makes it prohibitive with respect to cost for the general case. As a result, testing in one dimension is done as principal stresses and strains may be identified pretest, and required measurements are determined by using the equations for conservation of mass and momentum. The other major requirement for any field testing is redundancy of the measuring gages in order to assure a good statistical sample.

Testing in all three one-dimensional coordinate systems--planar, cylindrical and spherical--has been done for material properties although spherical testing had not been done in dry alluvium. Each test has its advantages and disadvantages and consideration was given as to the type of information desired before planning the in situ test. Figure 5 shows the three test types which are described below. For determining the constitutive equations, the following equations can be used with Lagrangian coordinates.

$$\frac{\rho_o}{\rho} = \frac{r}{h}^{n} \left.\frac{\partial r}{\partial h}\right|_t \qquad \text{Conservation of Mass (1)}$$

$$-\rho \left.\frac{\partial u_r}{\partial t}\right|_h = \left.\frac{\partial u_r}{\partial \theta}\right|_t + n\frac{\phi}{r} \qquad \text{Conservation of Momentum (2)}$$

$$u_r = \left.\frac{\partial r}{\partial t}\right|_h \qquad (3)$$

where

ρ_o = density, subscript o indicates initial bulk density
r = range (not a constant)
h = Lagrangian coordinate (initial gage location)
t = time
u_r = velocity (in the principal stress direction)

$$n = \begin{cases} 0 & \text{planar} \\ 1 & \text{cylindrical} \\ 2 & \text{spherical} \end{cases}$$

While obtaining field data, the strain paths over which the stress versus strain curves are finally derived are important. Figure 6 (Ref. 4) illustrates the strain paths observed from calculations of a nuclear surface burst. There appear to be two

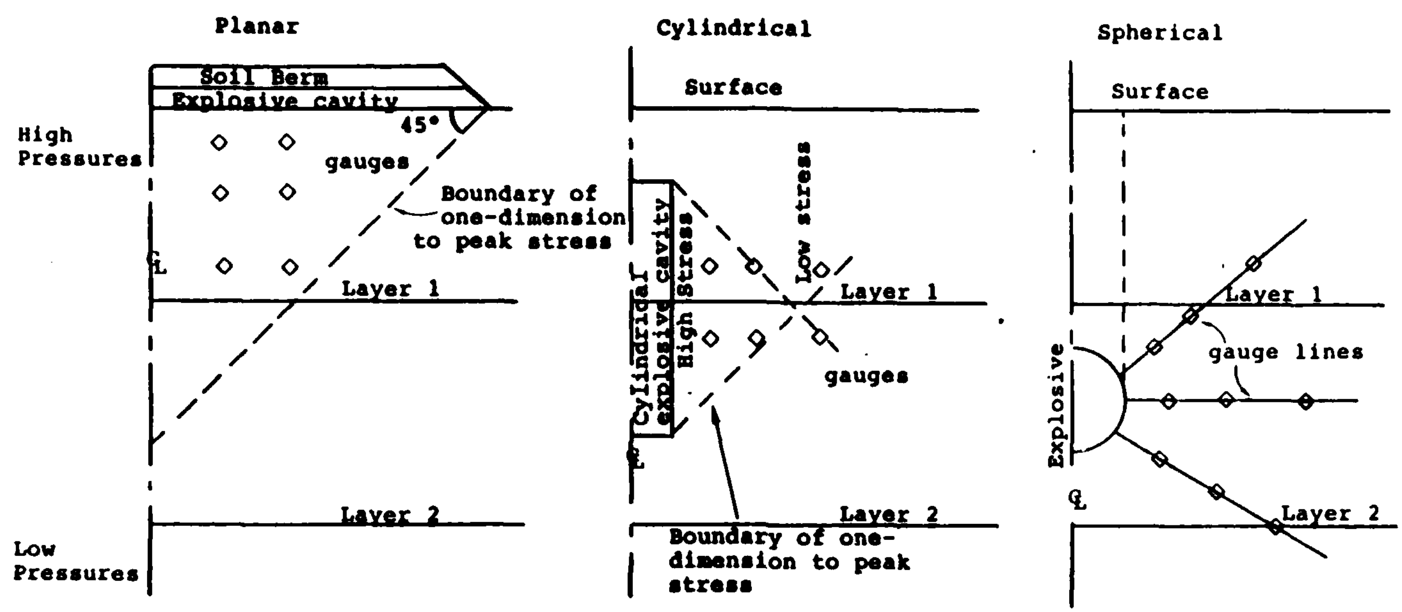


Figure 5. Geometries for the three in situ material properties tests

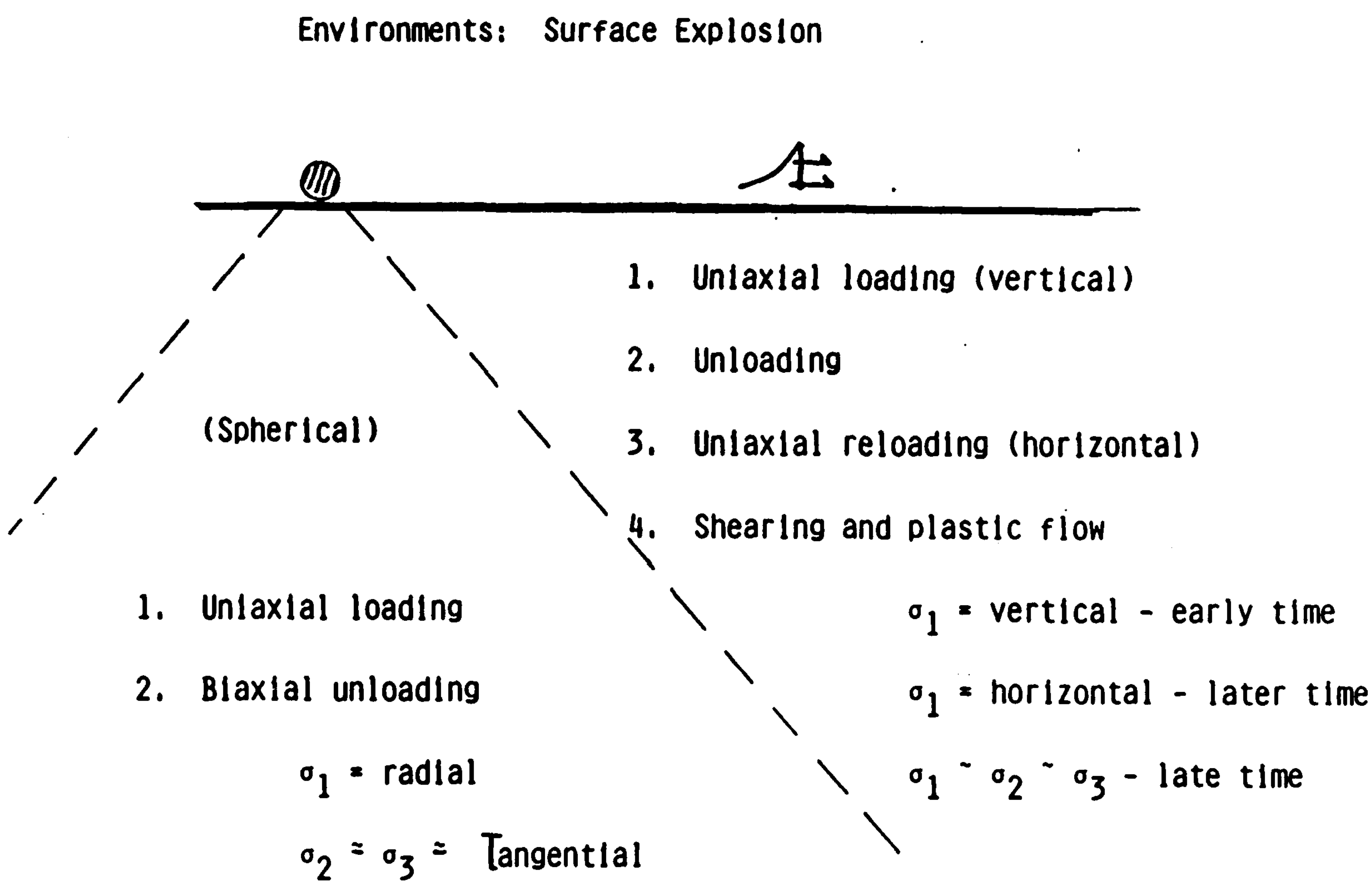


Figure 6. Strain path identification for a nuclear surface burst

major volumes of interest: (1) directly beneath the source including the volume mapped out by a cone subtending at a 45° angle with respect to the surface, and (2) the area subjected to surface airblast first followed by shearing and plastic flow.

The area just beneath the surface initially has uniaxial strain loading followed by complicated principal stress rotations, shearing and other two-dimensional effects. It is suggested that, except for initial crush-up, one-dimensional tests could not follow these complicated motions. Contrasted with this, the less complicated motion is the central area beneath the charge. In this area the motions are mostly spherically one-dimensional.

A one-dimensional field test was chosen because the principal stresses and strains are known a priori and could be directly measured. The choice of which kind--planar, cylindrical, or spherical--was made based on nuclear surface burst strain paths and limitations posed by the tests themselves. Short test descriptions, their good features and limitations, are given below.

DISC (Dynamic In Situ Compressibility) Test (Ref. 8) (Fig. 5a). The surface is loaded with an explosive beadfoam mixture covered with soil, tailored to produce desired peak pressures and durations. The soil under the explosive is compressed in uniaxial strain until effects of the lateral edge arrive in the test-bed. By measuring either stress or velocity-time histories, complete uniaxial strain loading curves can be directly calculated. Later in time, when the edge effects become important, estimates of shearing properties may be obtained by comparing results of two-dimensional calculations with the experiment. Some drawbacks of this type of test are: it is difficult to test other than the surface material; the test and its analysis become more complicated if there is substantial layering within the test-bed; to sample deeper depths requires increase of the lateral extent of the explosive driver; and deeper materials are always sampled at lower stresses than shallower material. Its advantages include: it directly replicates the strain paths caused by the airblast of a device and it is also fairly simple to field.

CIST (Cylindrical In Situ Test) Test (Ref. 9) (Fig. 5b) is basically a vertically oriented cylindrical explosive source. Measurement of both velocity and multidimensional stress-time histories are required to describe the state of the material. The explosive charges used have been detcord in an air cavity. This produces a low pressure stress-time history boundary. If higher stresses were to be required, pure explosive may be used. Because of the present inability to measure other than the maximum principal stress-time history, direct determination of the constitutive relationships has never been accomplished to complete satisfaction. Rather, the material properties have been estimated by comparison with parametric one- and two-dimensional code calculations. Contrasted with the DISC, the CIST has the ability to test individual horizontal layers at different depths. In addition, CIST will subject each depth to both high and low stress levels. As in the DISC test, the ends of the explosive cylinders introduce two-dimensional effects that perturb the one-dimensional flow field. Also, a direct estimate of the equation of state has not been available. There have been 23 tests on several different types of materials, including alluvium, wet soil, weak rock, and hard rock.

In designing this material properties test, these two types of tests were eliminated because:

a. DISC tests give loading estimates only for one-dimensional uniaxial strain. Shearing properties can be obtained only when two-dimensional effects perturb the flow field and these cannot be simply reduced or calculated. In addition, it was felt that sampling near surface material was a drawback.

b. The CIST test was not used primarily because analysis indicated that, to uniquely determine the stress versus strain properties, hoop stresses were required to be measured. These could not be measured; thus, estimates could be obtained only from code iterations.

Thus, the spherical test (Ref. 10) was chosen to obtain material properties. The strain paths were identical to some zones of a nuclear surface burst. It was thought that required measurements of radial velocity and radial stress could be measured. Any depth could be addressed. It would give shearing estimates through spherical expansion. Reference 11 sums up the important constraints for the spherical tests. They require measurements of only radial stress and radial velocity. Both stress and strain tensors are completely defined (this measurement can be predefined). The testing procedure appears to be quite straightforward. On the negative side, a truly spherical source is hard to emplace without destroying symmetry. The spherical source must be emplaced in a homogeneous test-bed with no surface effects or layers destroying symmetry. Strain paths from spherical tests are directly applicable only for the area beneath the surface burst where the stress field is nearly spherical; however, results should give initial loading estimates valuable to the near surface airblast from surface bursts.

SPHERICAL MOTIONS

Being a one-dimensional test, reduction of Equations 1, 2 and 3 to give the required information directly becomes straightforward. For excellent discussions of requirements and results in rock, References 11, 12 and 13 are recommended. In particular, the strains may be calculated from radial displacements (usually obtained from integrated velocity gages or doubly integrated accelerometers) by:

$$\varepsilon_r = \left(\frac{\partial u_r}{\partial h} \right)_t \tag{4}$$

$$\varepsilon_\theta = \varepsilon_\phi = \left. \frac{u_r}{h} \right|_t \tag{5}$$

$$\varepsilon_v = \left. \frac{\left(h_2^3 - h_1^3\right) - \left(r_2^3 - r_1^3\right)}{\left(h_2^3 - h_1^3\right)} \right|_t \tag{6}$$

where

ε_r = radial strain

ε_θ = tangential strain

ε_v = volumetric strain

$u_r = \int_{t_o}^{t} v_r dt$

h = Lagrangian coordinate (in this case it is taken as a gage position and path)

t = time$_o$

r = radius from charge

When the original design was put together, the consensus was that radial stress and velocity must be measured directly and hoop stresses could be calculated from

$$\sigma_\theta = \sigma_r - \rho \frac{r}{2} \left[\left(\frac{\partial v_r}{\partial t} \right)_h - \frac{r^2}{h^2} \frac{1}{\rho_o} \left(\frac{\partial \sigma_r}{\partial h} \right)_t \right] \tag{7}$$

where

ρ_o = initial density

ρ = present density

v = velocity

This equation is straightforward; however, a derivative of the velocity (or acceleration) is required, and since both radial stresses and velocities are used together, accurate timing between the two is required. As will be seen, these two constraints made it virtually impossible to calculate stress differences for early times, especially during the initial loading of the material. As the gradients become less steep, later time estimates of stress differences are more accurate.

An extremely important analysis tool resulted from J. Trulio's development of a stress-bound formula (Ref. 14). The formula allows calculation of radial stress bounds using radial velocity measurements and taking reasonable limits for stress differences. Namely, the stress differences include no stress differences (hydrodynamic), Mohr-Coulomb failure, or von Mises failure criteria.

Figure 7 shows the geometry. Simple geometric arguments eloquently applied give limits of radial stresses to be at the gage

$$\int_{r_g}^{r_f} \rho a dr \le \sigma_r^g \le \int_{r_g}^{r_f} \left(\frac{r}{r_g}\right)^{n\beta} (\rho a + nk/r) dr \tag{8}$$

$$= \frac{k}{\beta} \left[\frac{r_f}{r_g}^{n\beta} - 1 \right] + \int_{r_g}^{r_f} \left(\frac{r}{r_g}\right)^{n\beta} \rho a dr \tag{9}$$

where

$$n = \begin{cases} 0 & \text{uniaxial} \\ 1 & \text{cylindrical} \\ 2 & \text{spherical} \end{cases}$$

a = acceleration

compressive stress > 0

Shear-strength limit: $\sigma_r - \sigma_\theta \le \min (c + bP, Y_{rm})$

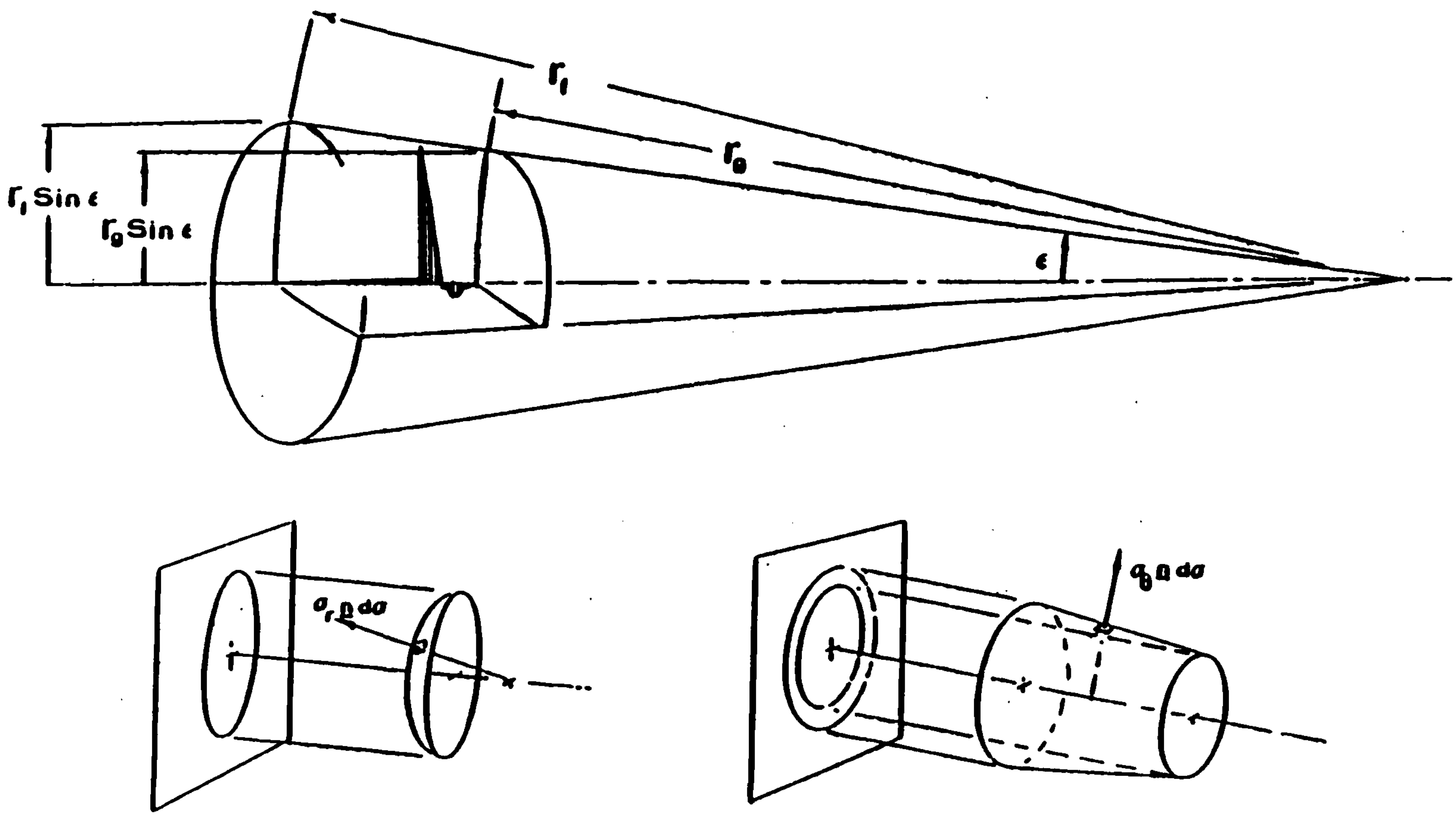


Figure 7. The narrow cone in which spherical motion is defined (top) and axial projections of areas on which principal stresses act (bottom) (From Ref. 14)

$$\beta = \begin{cases} 1 & \text{tensile failure} \\ b/\left(1 + \frac{2}{3}b\right) & \text{Mohr-Coulomb failure} \\ Y_{vm} & \text{von Mises failure} \end{cases}$$

f corresponds to the wave front

g corresponds to the gage

A lot of emphasis for a spherical shot was placed on the stress differences and shearing which were to be produced and analyzed. In slow rising stress fields and static analysis the material moves outward immediately upon application of the stress, and shear is produced because of the geometrical expansion. In a dynamic test, the phenomena appear to be different in important ways. Figure 8, taken directly from Reference 15, shows the strain paths for a spherical field of motion from contained shots. Note that during initial loading the path is along a uniaxial strain path. It is not until unloading that outward flow and shearing take place.

Implications from this are that a simpler one-dimensional <u>planar</u> analysis can be used during loading. The material properties derived for this test can be directly used for both beneath the charge motions and the planar 1-D airslap region.

It also implies that only velocity <u>or</u> stress need be measured, or if both are measured, checks can be made rather easily through the jump conditions, during loading, namely

$$\sigma_r = \rho_o c v_r \tag{10}$$

and their implications where c = propagation velocity and Equation 8 during unloading.

With the above equations, knowledge of the expected behavior, and a spherical test, construction of stress versus strain curves should be relatively easy. Simply construct the experimental waveform fields and invert for the material

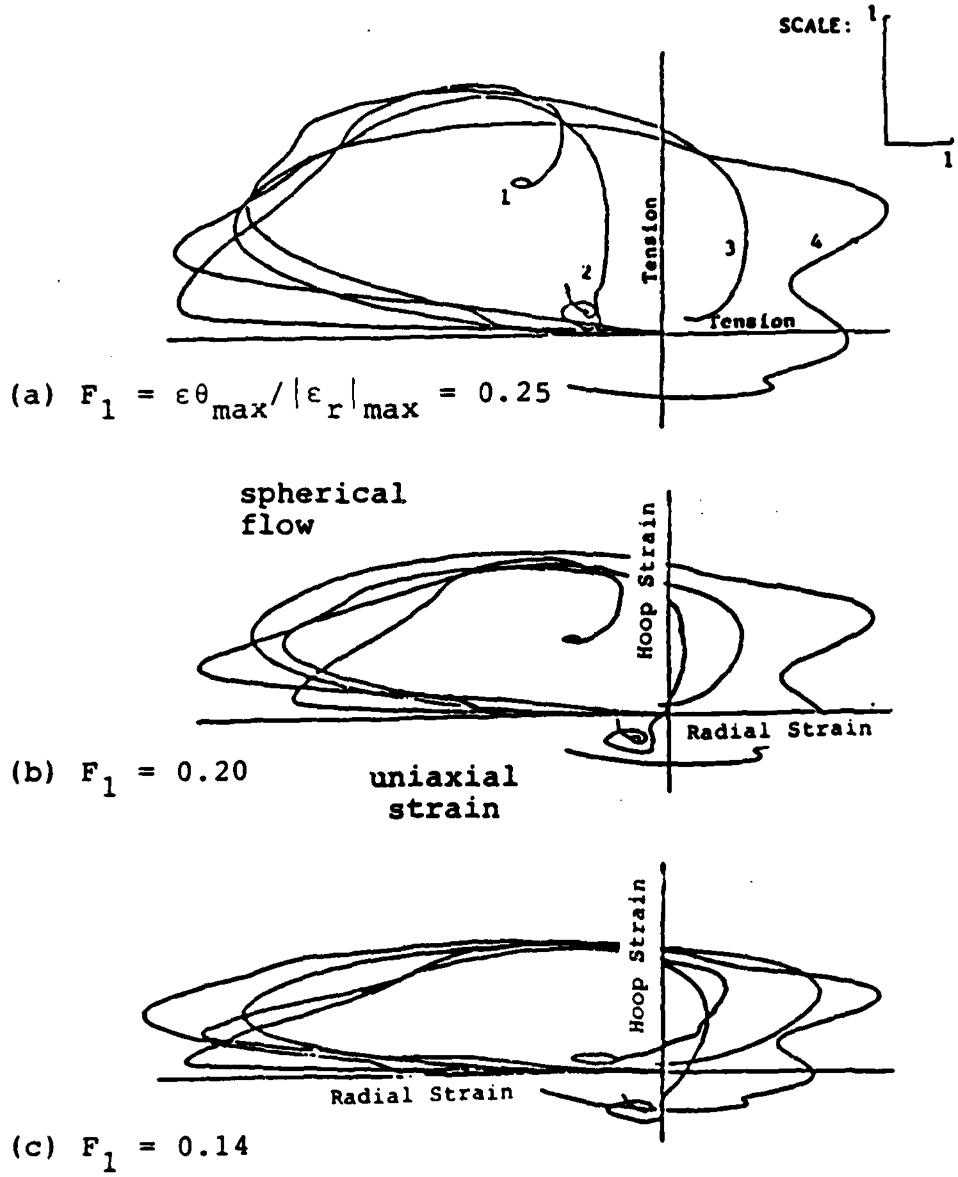


Figure 8. Typical strain paths obtained from traveling wave pulses for nearly spherical fields of motion from four deep shots. (Note the 2:1 expansion of the hoop strain scale) (From Ref. 15)

properties. Unfortunately, most of the test data have some inconsistencies and are not well validated. For example, if stress gage data are used to construct the curves, the result may be different than if velocity gages are used. The experiment then must be designed properly to give validated stress and velocity data.

MEASURING THE FIELD RESULTS

Physical fielding and as-built data are given in Reference 3. This section deals with what, where and why particular instrumentation was used.

Gage Line Orientation

The test layout began with work from Reference 15. To accurately measure inhomogeneities of any test site, and to make the necessary redundant recordings of the data to calculate accurate stress-strain curves, the primary silicate cell structure, the rhomboid, should be used for gage lines. That is, from the source, instrumentation lines radiating upward at 47° and downward at 47°, normal to each other would provide adequate information to deduce the sphericity and field velocity. Additional work concerning the placement was carried out by Trulio (Ref. 16). He suggested that, for spherical fields, there were particular orientations that could be identified that would lead to a minimum least squares error, in the first-degree field, relative to that of the second degree. That is, if the velocity (or stress) field is constructed using Surface Spherical Harmonics,

$$F_N = \sum_{n=0}^{N} \left\{ A_n P_n(\cos\theta) + \sum_{m=1}^{n} \left(A_n^{mc} \cos m\phi \right. \right.$$

$$\left. \left. + A_n^{ms} \sin m\phi \right) T_n^m (\cos\theta) \right\} \tag{11}$$

the orientation of gage lines can be made such that most information measured will relate to the first-degree field. The second-degree field is then oriented such that it does not appear to exist with respect to the gages. Reference 16 uses Gaussian Quadrature to define the orientation of the gage line. The solution implies that $\cos\theta = \pm 1/\sqrt{3}$.

Relationships were also developed for ϕ. For MP2, however, strict axial symmetry about the vertical Z-axis was assumed. This resulted from considerations of the geology and morphology of the site which was basically laid down in a horizontal manner. This assumption also implied that there could be major perturbations in the vertical direction and any measurements placed other than horizontally would show differences with respect to the horizontal lines and not lead to redundantly measuring a spherical field. (In addition, placement of the gages along the vertical proved to be beyond the test resources.) The analysis showed that gage lines should be placed with $\theta = \pm 35°$ with respect to some arbitrary axis, and that directions in ϕ were not important.

Other limiting factors were considered. These included the fact that stress gages required placement along a horizontal line (Ref. 17). Redundancy questions were addressed and at the higher stress levels, at least fourfold redundancy was required. Finally, to reduce azimuthal perturbations, all of the gage lines were to be placed in the same general horizontal sector ($\theta = 0 \pm 35°$).

The final orientation of the lines is shown in Figure 9 (from Ref. 14). Two lines were horizontal (135° and 195° radials) and centered on the charge. These were to contain the stress gages, and their validating velocity measuring devices. Two lines were placed at +35° with respect to the horizontal (165° and 225° radials), and the remaining one line was placed at $\theta = -35°$ (180° radial). This configuration was considered

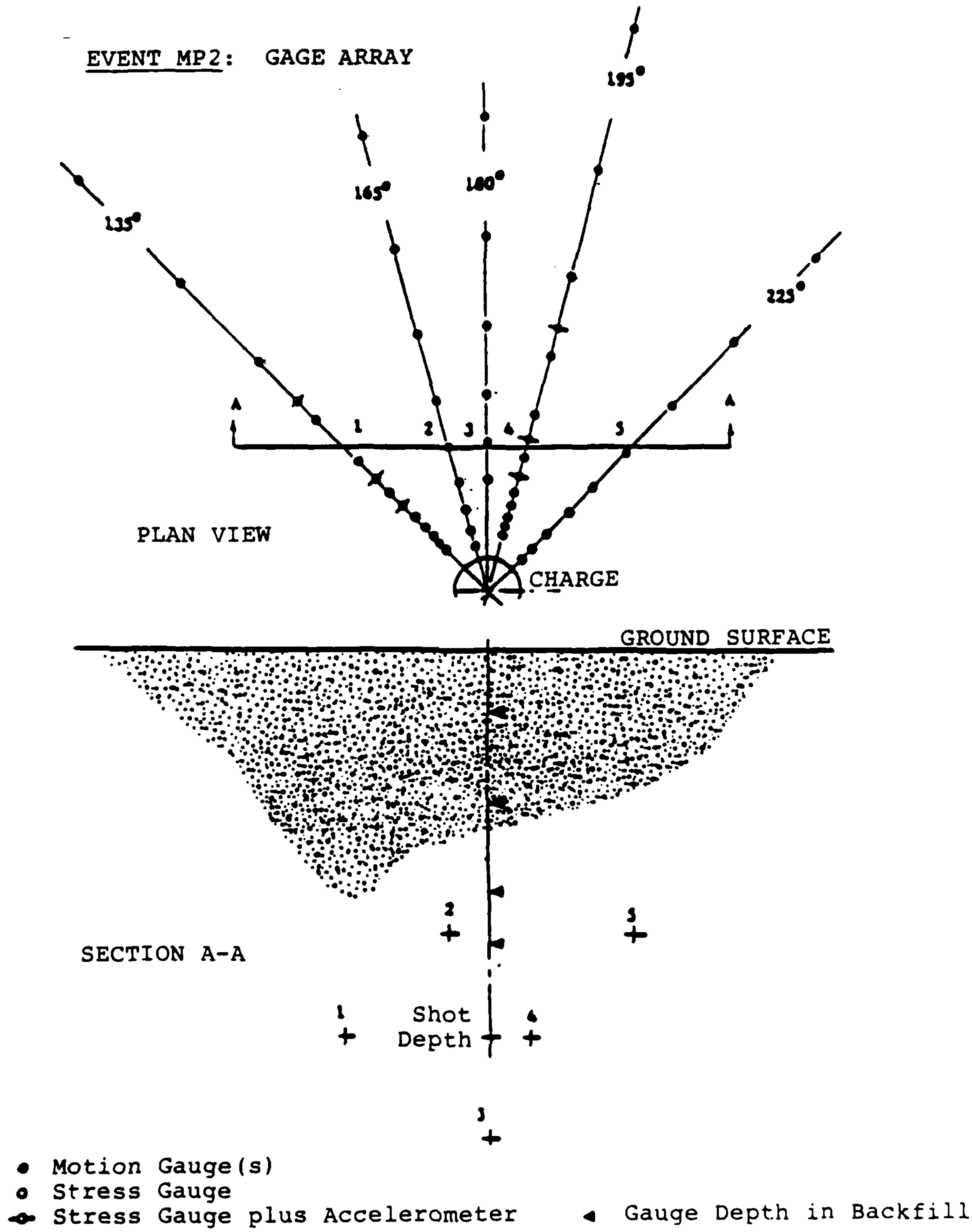


Figure 9. MP2 gage line layout (Ref. 14)

adequate, considering the feasibility and resources to measure the field with fivefold redundancy. In addition, it would define the first-degree field in spherical harmonics, neglecting dependency in ϕ.

It was noted that the gage configuration could determine the first-degree term of spherical harmonics. If this term was small, the test could be considered spherical and the test could be analyzed using the momentum and mass conservation equations (Eqs. 1-3). If the first-degree term showed that the test was nonspherical, then it was not clear what to do with the data. Estimates of the stress-strain curves could be obtained, but these would be subjected to some unknown error. If the site proved to be highly anisotropic in the vertical direction, the fivefold redundancy would be reduced to only twofold (two lines up or two lines at the horizontal), which was considered inadequate considering gage failures. Thus, a quandary resulted pretest--the fivefold redundancy was required for gage survival questions; but if the shot proved nonspherical, there would be insufficient data. Fortunately, the test proved to symmetric out to a range of 10 or 16 m, based on time of arrival considerations and tangential measurement, and the redundancy was obtained.

Positions of the Gages

Along any one line, positions of the gages are important. The requirement for stress-strain estimates for 1 GPa to 1 MPa basically dictated the positions and gage types. General guidance from Reference 15 set particular ranges by dictating four measurements per decade of velocity, where required to know velocities (or stresses) to within 10% through linear interpolation. This set the gage slant ranges at 3.0, 3.7, 4.0, 5.3, 7.1, 9.5, 12.6, 16.8, 22.5 and 30 m. These ranges provided extension in stresses beyond the 1-MPa limit; however, 1 GPa was considered the upper limit for any measurement.

Consideration was also given to validating both stress and velocity records by considering momentum and impulse checks. It was thought that, if a stress gage was placed between velocity gages, then the momentum recorded passing through the velocity gage can be compared with the differences of impulse recorded by the two stress gages. This directed that stress gages be placed at radial ranges of 3.0, 3.4, 4.6, 6.2, 8.2 and 14.0 m. The relationships for momentum and impulse checks are straightforward for planar geometry; however, they require measurement of tangential stress in spherical geometries. Since tangential measurements could not be made, the staggering of stress gages with respect to velocity gages did not substantially improve data validation efforts. It would have been better to place stress gages at the same ranges as the velocity gages for this test.

Selection of gage types also proved to be a major problem because of the high velocities and stresses. For stresses above 0.1 GPa steel-armored flatpack carbon and ytterbium gages were the only type available (Ref. 17). Below 0.1 GPa, only diaphragm stress gages were available. Velocities above 100 m/s could not be measured, and only an occasional measurement above 50 m/s in alluvium had been measured previously. For these measurements, hard-mounted accelerometers were employed. MP3 showed good survival of the hard mounts (Ref. 2). The nature of the material-gage interaction was such that accelerations recorded for 80 m/s were on the order of only 50 kg. Again, the real parameter of interest was strain, or differences in displacements, and doubly integrating accelerometers to obtain displacements was considered unreliable. Unfortunately, the only reliable velocity gage (the DX velocimeter) can be used only at accelerations less than 1000 g. However, where possible, these were to be used to give late-time displacements for comparison with the accelerometers. To ascertain spherical symmetry, nonradial motion gages were also recommended at most ranges.

A summary of the gage requirements leads to 10 ranges for five lines measuring radial stress, radial accelerations, radial velocities (where possible) and tangential velocities. Total measurement count was approximately 190. Table 1 (from Ref. 14) lists positions and types of gages. Details for emplacement and fielding are contained in References 1, 2 and 3.

TABLE 1. NOMINAL LOCATIONS OF MP2 GAGES (Ref. 14)

SLANT RANGE (m)	GAUGE NO.	AZIM. (deg)	TYPE OF GAUGE
LINE 1; ELEVATION=0°			
3.0	5007-8	90	SR
	5001-2	135	SR
3.45	5034-5	105	SR
	5036-7		Sϕ
4.0	1301-2	125	aR,Z
	2001	125	UR
	5059	315	SR
4.62	5040-1	110	SR
	5042-3		Sϕ
5.3	1304-6	135	aR,Z,ϕ
5.5	5060	315	aR
6.16	5046-8	125	SR
	1424	125	aR
7.1	1307-9	140	aR,Z,ϕ
	2004-5		UR,Z
8.21	5049-51	127	SR
	1427		aR
9.5	1310	135	aR
	2007-8		UR,Z
12.6	1313	135	aR
	2010-2		UR,Z,ϕ
14.0	5052-4	130	SR
	1430		aR
16.8	1316	135	
	2013-4		UR,Z
22.5	1319	135	aR
	2016-8		UR,Z,ϕ
30.0	1322	135	aR
	2019-20		UR,Z

SLANT RANGE (m)	GAUGE NO.	AZIM. (deg)	TYPE OF GAUGE
LINE 3; ELEVATION=35-1/4°			
7.1	1397,9	180	aR,ϕ
	2085-6		UH,Z
9.5	1400	180	aR
	2088-9		UH,Z
12.6	1403	180	aR
	2091-3		UH,Z,ϕ
16.8	1406	180	aR
	2094-5		UH,Z
22.5	1409	180	aR
	2097-9		UH,Z,ϕ
30.0	1412-3	180	aR,ϕ
	2100-2		UH,Z,ϕ
LINE 4; ELEVATION=0°			
3.0	5004-5	195	SR
3.45	5013-4	212	SR
	5015-6		Sϕ
4.0	1325-6	185	aR,Z
	2022	185	UR
	5032	45	SR
4.62	5019-20	207	SR
	5021-2		Sϕ
5.3	1328-30	195	aR,Z,ϕ
5.5	5033	45	SR
6.16	5025-7	205	SR
	1415		aR
7.1	1331-3	190	aR,Z,ϕ
	2025-26		UR,Z
8.21	5028-30	202	SR,Z,ϕ
	1418		aR
9.5	1334	195	aR
	2028-9		UR,Z
12.6	1337	195	aR
	2031-3		UR,Z,ϕ
14.0	5056-8	199	SR
	1421		aR
16.8	1340	195	aR
	2034-5		UR,Z
22.5	1343	195	aR
	2037-9		UR,Z,ϕ
30.0	1346	195	aR
	2040-1		UR,Z

SLANT RANGE (m)	GAUGE NO.	AZIM. (deg)	TYPE OF GAUGE
LINE 5; ELEVATION=35-1/4°			
3.66	5010-1	279	SR
4.0	1373,5	235	aR,ϕ
	2064-5		UH,ϕ
5.3	1376,8	225	aR,ϕ
7.1	1379.81	230	aR,ϕ
	2067-6		UH,ϕ
9.5	1382	225	aR
	2070-1		UH,Z
12.6	1385	225	aR
	2073-5		UH,Z,ϕ
16.8	1388	225	aR
	2076-7		UH,Z
22.5	1391	225	aR
	2079-81		UH,Z,ϕ
30.0	1394	225	aR
	2082-3		UH,Z
BACKFILL; 1m OFF ϕ			
4.98	1433	225	aZ
7.62	1435	139	aZ
12.25	1437	225	aZ
16.83	1439	139	aZ
LINE 2; ELEVATION=35-1/4°			
4.0	1349,51	155	aR,ϕ
	2043-4		UH,ϕ
5.3	1352,4	165	aR,ϕ
	2046-7		UH,ϕ
7.1	1355,7	160	aR,ϕ
9.5	1358	165	aR
	2049-50		UH,Z
12.6	1361	165	aR
	2052-4		UH,Z,ϕ
16.8	1364	165	aR
	2055-6		UH,Z
22.5	1367	165	aR
	2058-60		UH,Z,ϕ
30.0	1370	165	aR
	2061-2		UH,Z

TEST OBJECTIVES

As stated, the primary objective of this test was to provide stress and velocity data from 1 GPa to 1 MPa along a controlled (spherical) load-unload path for use in determining in situ material behavior relevant to the CARES program. The objective is rather simple but led to major differences in ways material properties were achieved.

Two approaches were taken during the analysis. One approach was to evaluate the stress versus strain curves directly from the data. This involved calculating strain from the motion fields and plotting them versus the stresses either measured or bounded from the velocity data. The second approach was to determine the stress-strain relationship through numerical calculations of the test. In this method, finite difference calculations were made both before and after the test. The material model parameters were varied until the velocity and/or stress-time histories produced by the code gave the "best agreement" with measurements on the test. The model that produced the best agreement was then said to have the correct stress-strain relationship.

For determining the material properties, several participants were tasked to provide an analysis. The participants held their own views and objectives for analysis. Below is a synopsis of these objectives, listed alphabetically by organization.

a. Air Force Weapons Laboratory (AFWL). AFWL was tasked to field the test. In addition, AFWL, with the help of the New Mexico Engineering Research Institute (NMERI), wanted to directly solve for the constitutive relationships directly from Equations 1, 2, and 3. They proposed to do this with the help of the Lagrangian Analysis of Stress and Strain (LASS) (Refs. 12 and 13). The analysis required using both the stress- and velocity-time histories. It was thought that effects of loading rates and estimations of stress difference limits (then an important parameter) could be addressed.

b. Applied Research Associates (ARA). ARA was to address the applicability of using empirical estimates for site specific estimates. In addition, ARA, with support from the Air Force Office of Scientific Research (AFOSR) addressed a calculational material model developed by parametric studies.

c. Applied Theory, Inc. (ATI). ATI suggested the original test and helped in field design. Their analysis was to use velocity and stress data, again to directly evaluate a material model. In particular, they were to measure stress versus strain curves on truly spherical strain paths, in situ. They also analyzed in detail the accuracy of stress gage output in order to aid stress gage development; evaluate sample-and-lab-test procedure and furnish stress-strain input to material models. As already stated, several important mathematical relationships were developed by ATI. One of the more practical ones calculated stress bounds using velocity data.

d. California Research and Technology (CRT). CRT's primary objective was to fit the laboratory stress-strain data with a simple material model, thus providing a standard by which more elaborate and/or sophisticated models could be judged (Ref. 18). They had a rather unique outlook. Given a less expensive type of soil model testing, could substantial improvement be made from in situ testing? In addition, they elected to use a rather simple material model, the AFWL stick model (Ref. 19), to address the question whether or not more sophisticated modeling was required.

e. Pacifica Technology (PACTECH). PACTECH wanted to address a rate-dependent model for this site. Their model for this site included a type of rate effect defined as a Standard Linear Solid. The long rise times to peak velocity observed on

MP1 and a cylindrical material properties test, CIST 18S (Ref. 20), motivated the use of this type of model (Ref. 21).

To sum up the various work, AFWL and ATI attempted to directly invert the stress and velocity data into stress versus strain estimates. CRT and PACTECH were to develop, or back out through calculations, material models from calculations. CRT addressed the question of what is really gained from in situ testing. ARA was to assess the empirical data base with respect to a particular site.

RESULTS

The intent of this report is not to give a detailed gage by gage description of field results nor present an additional analysis to add to those already done. Rather, a short description is given of the data which was considered reliable enough to be used in the several analyses. Then, summaries of each participant's analysis, taken directly from their reports, are presented. Several conclusions, drawn from the summaries, will be discussed.

DATA USED

Reference 3 reports using a total of 178 gages, broken down into accelerometers (66), velocity (66), and stress (46) gages, to measure the field. The attempt to measure tangential stresses failed because of improper pretest prediction gage ranging. All of the velocity gages gave ambiguous records. The shape was correct; however, the recorded velocity levels were inconsistent. Time-of-Arrival (TOA) arguments indicated that the shot was spherical, and, although data were obtained, tangential acceleration measurements were of little importance, other than that they recorded motion. The radial stress and radial accelerations provided most all of the information for analysis. The data set was reduced to 23 accelerometers and 22 stress records (a total of only 49 records out of the 179 recorded). With these data, material models were developed and an attempt at gage validation was justified. This low number of records used could suggest that future tests might have fewer gages than used in this test. The ratio of usable to fielded gages was quite good for these particular gages. For stresses up to 100 MPa, approximately 80% of the accelerometers and stress records gave usable data.

Much was said concerning the ambiguity and ultimate nonuse of all of the DX velocity gages. The fielded plan specifically placed these gages where data recovery was expected (accelerations $\leq$ 1000 g) with the exception of one range which was above the DX gage limits where survival was expected. Almost all of the DX velocity gage packages reported velocity traces nearly identical to the integrated accelerometers with respect to shape. The amplitudes, however, were different by as much as 100% when compared. Extensive analysis of the gages themselves showed no absolute reason for the calibration problems, although temperature control of the gages is thought to be responsible for some of the problems. What is of concern is the fact that the MP2 DX velocity data taken by itself produced data scatter that is similar to that produced in older tests. It makes one question the absolute validity of DX results from earlier tests.

Data traces for integrated accelerometers and radial stress gages are given in Figures 10, 11 and 12. Velocity data were obtained for ranges greater than 5.2 m (100 MPa). Stress data were obtained for ranges greater than 3 m (1 GPa).

Times of arrival for various portions of the time histories are plotted in Figure 13. These include absolute TOA of any motion--at lower stresses this is the precursor and gives the seismic velocity (950 m/s). At higher stress this is the main stress wave and reflects the shock loading ($940 < C_L < 1500$ m/s). At a range of approximately 7 m, the velocity pulses appear to disperse and the sharp rise in velocity (main stress pulse) separates from the elastic precursor. This sharp rise is plotted as is the arrival of peak velocity, giving the so-called "loading velocity" ($\approx$ 220 m/s).

Figure 14 shows the peak velocities obtained from the integrated accelerometers. At ranges greater than 8 m or so, the data can be fitted with a straight line. Reference 22 shows that more improvement (reduced errors in a least squares sense) can be made by using a higher degree of freedom fit. At ranges closer than 8 m, there appears to be a falloff in the data, suggesting

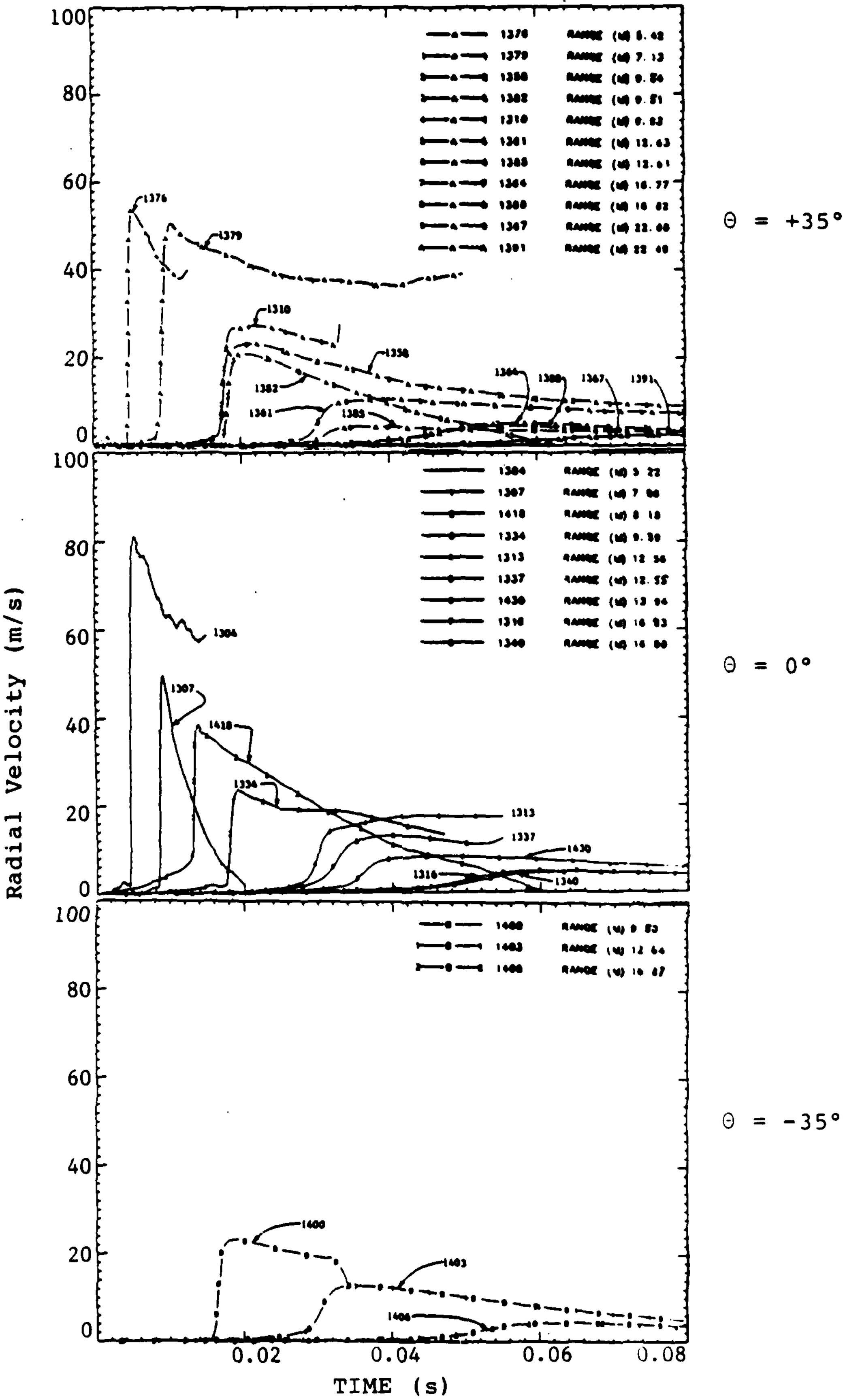


Figure 10. <u>Radial velocity traces for MP2</u>

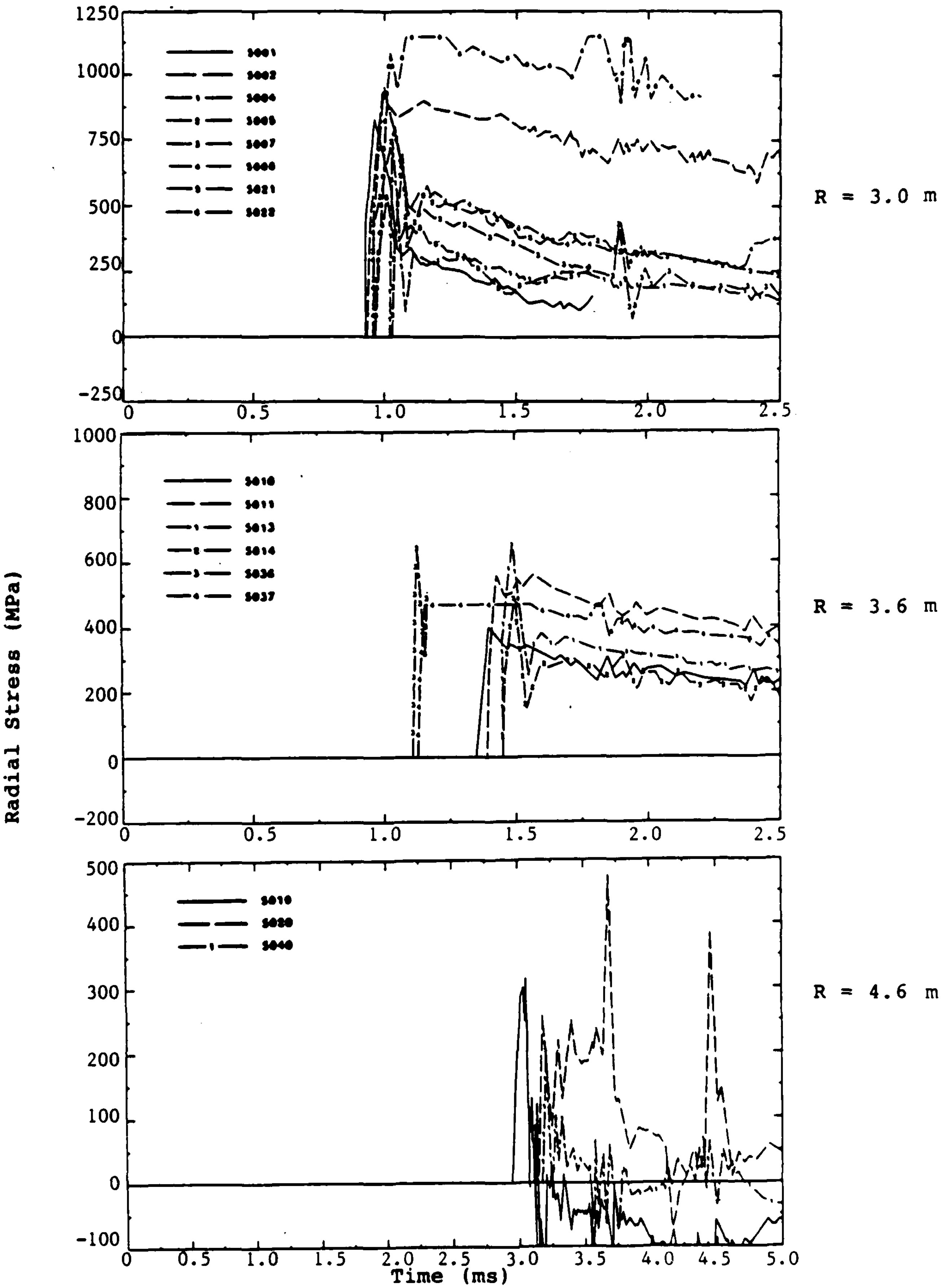


Figure 11. Radial stress (flatpacks) traces for MP2

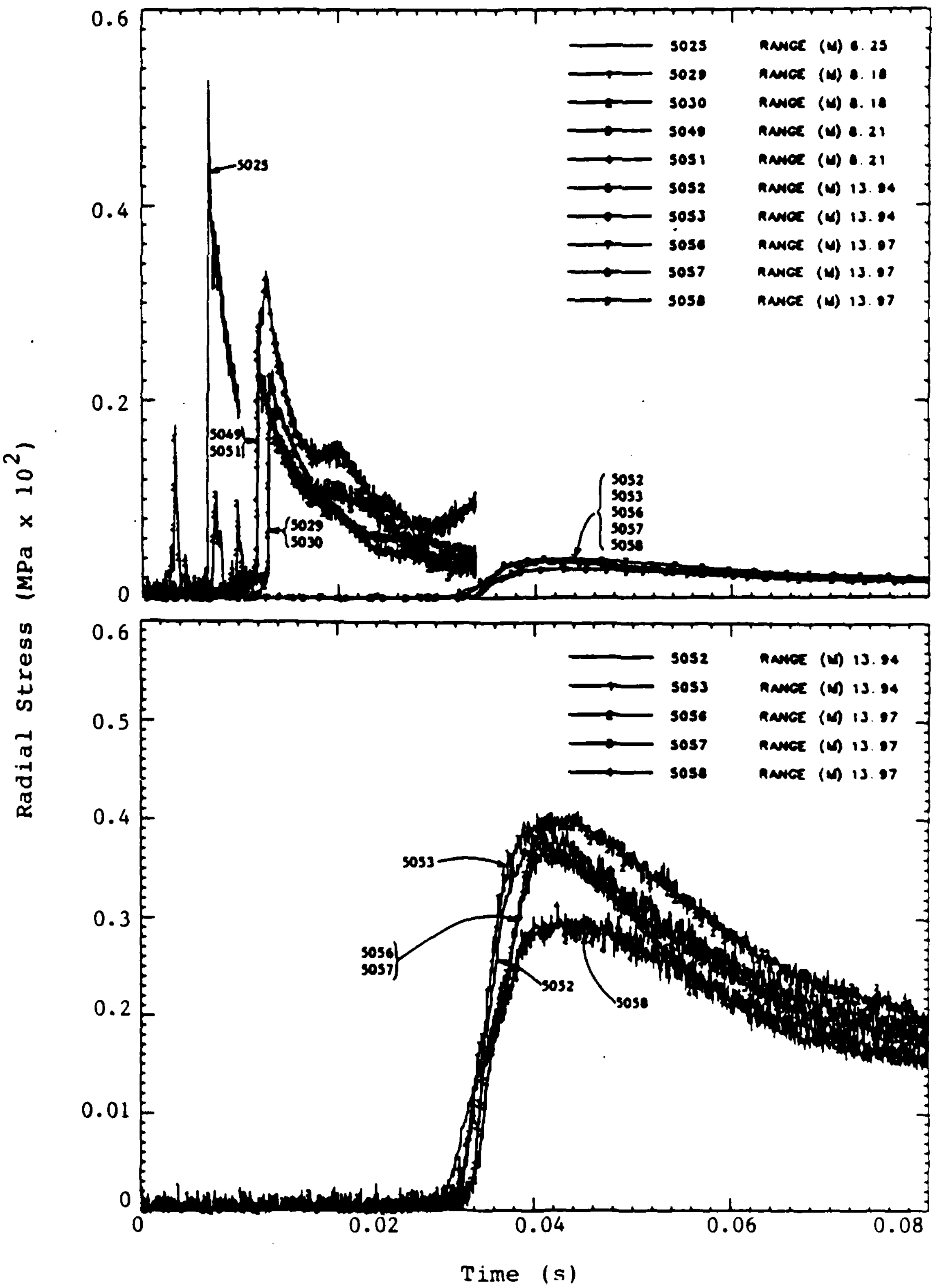


Figure 12. Radial stress (HRSE) traces for MP2

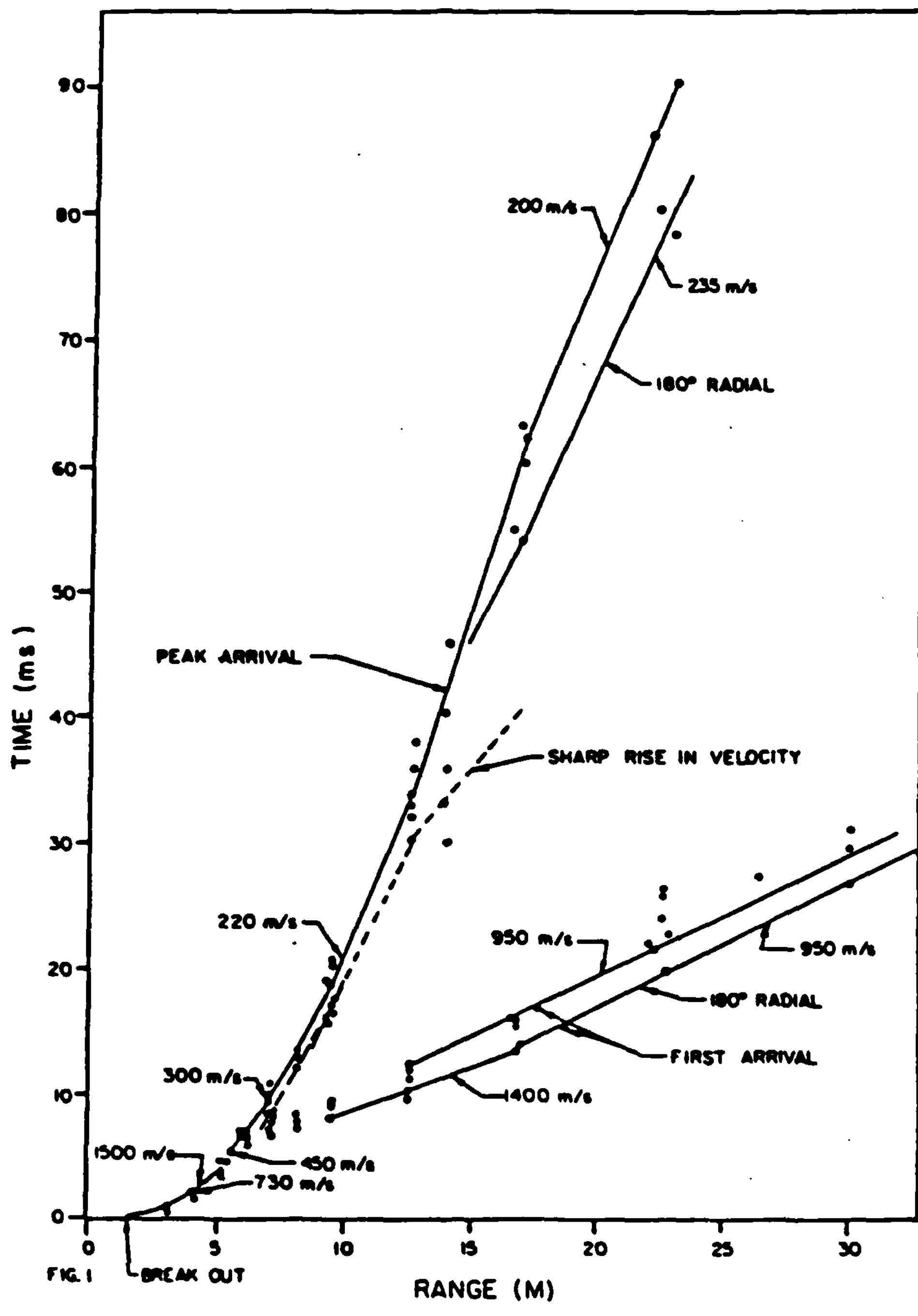


Figure 13. Time of arrivals of the stress and velocity records

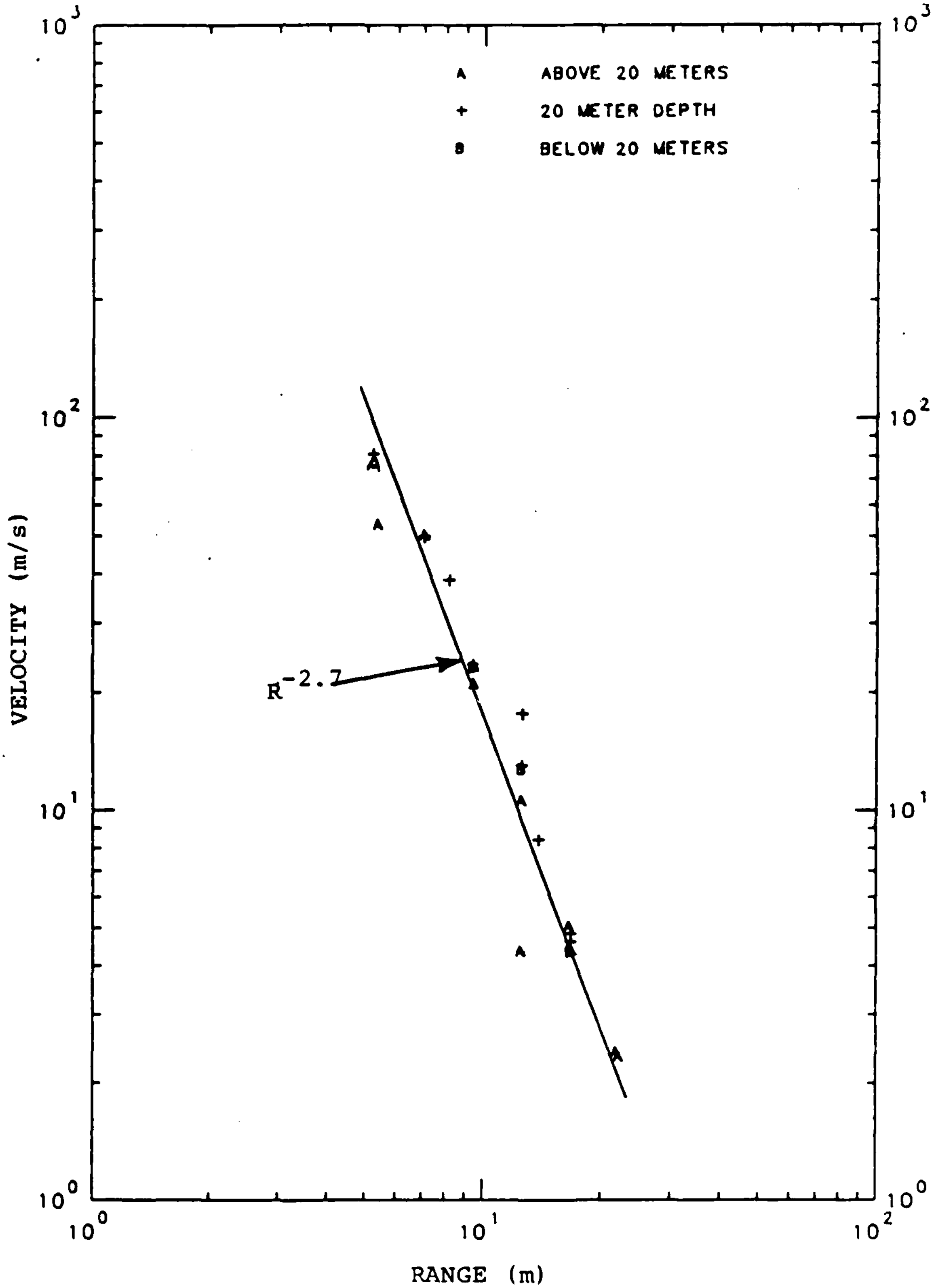


Figure 14. Peak radial velocity versus range from the MP2 accelerometer records

that a straight line should not be used. Note that all of the data at the 5.4 m-range are below the straight line fit. If these data are believed, a higher attenuation rate could be fitted to the data farther out than 8 m, and a lower attenuation rate fitted to the close-in data. Unfortunately, the 5.4-m data is the closest-in velocity data and does not warrant a firm conclusion concerning the degree of freedom. Peak velocities at all recorded ranges produce a mean with only $\pm$15% standard error. There is no real distinction between the five lines of data. Although this error is high for some types of analysis, it is one of the better sets of data for alluvium.

Figure 15 shows the peak stress versus range data for both the near source flatpacks and farther out HRSE diaphragm stress gages. The flatpacks (pluses) appear to form a consistent set of data. The HRSE also appear to form a consistent set, but between the two sets there is no overlap and the resulting slopes of the two sets are not the same. On the one hand, as is reported later, simple shock analysis of velocity data indicates that the peaks from the flatpacks are too high. But, where there is no overlap is precisely the range where Reference 23 suggests a change in slope of the peaks because of the fast traveling release wave.

Generally, the velocity-time history data below velocities of 30 m/s appears to be reproducible and self-consistent. The sharp rise to peak velocity is preceded by an elastic precursor. Directly after the initial sharp rise, the peak velocity may or may not have been reached. Many pulses appear to level off with perhaps a small increase (or decrease) of velocity. In all cases beyond a range of 8 m, the velocity pulse at closer ranges always exceeds those at farther ranges. For a planar geometry with a bilinear, no-recovery material (dry alluvium), velocity pulses at farther ranges are always a subset of pulses at closer ranges. MP2 data suggest continual radial compression after peak velocity is reached, which is a direct result of the spherical geometry.

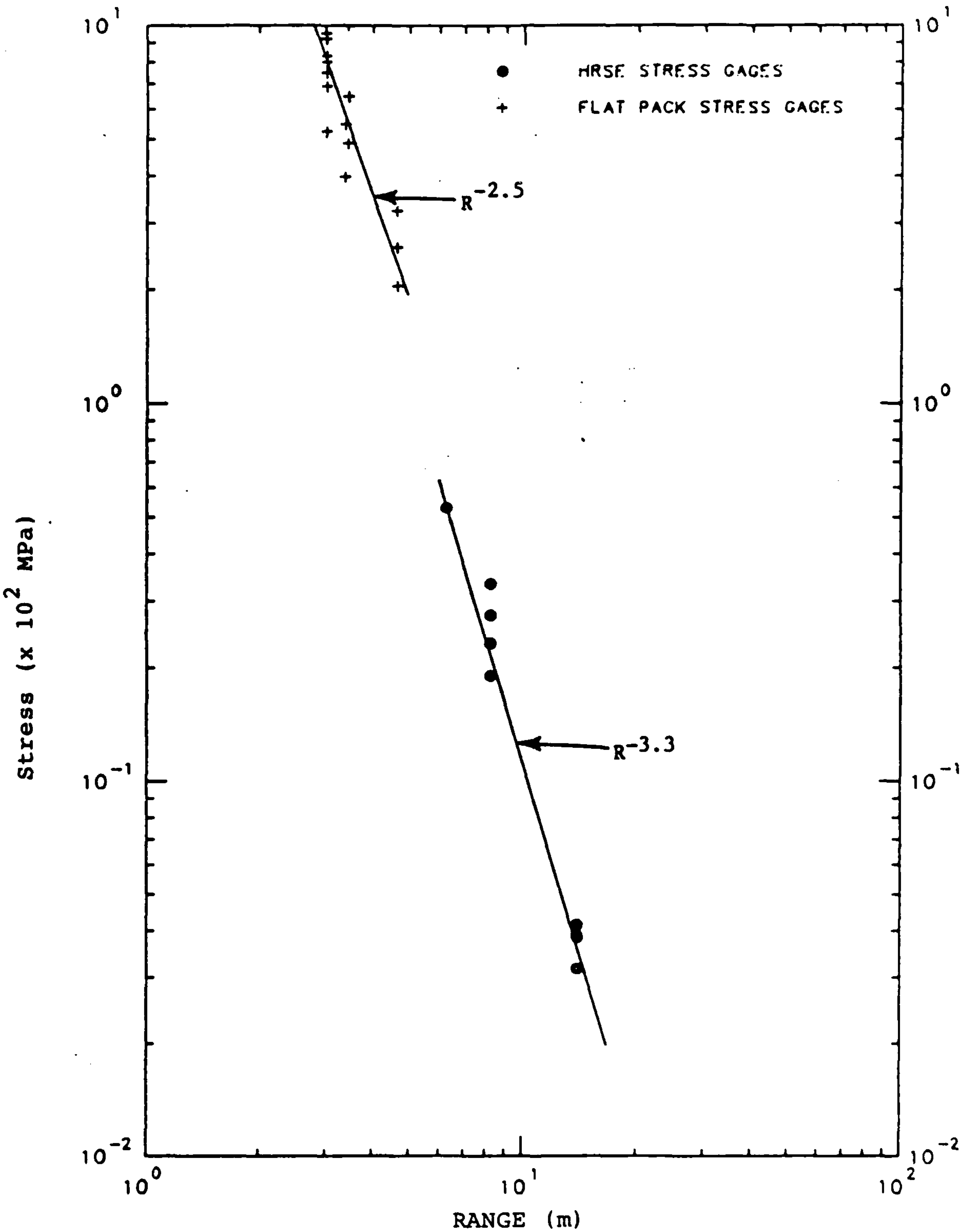


Figure 15. Peak stress versus range from the flatpack and HRSE gages in the MP2 test

Volumetric compression after peak velocities may or may not increase, but is dependent upon the velocity decay. This is the one important feature that cannot be made self-consistent between traces of the velocity or stresses and is important because it leads to late-time strain estimates through displacement differences.

Closer in than 9 m, the data are more scattered, although there are some consistent comparisons to be made. At the closest range, peaks range from 80 m/s to 58 m/s ($v = 72$ m/s, $\sigma = \pm 17\%$). Although the differences appear to be quite high, the standard error is only ±20% and makes one of the better data sets available for a spherical, dry alluvium event. The major disappointment with the velocity data is the very different character of the velocity decay, especially at the 7.1-m range. More is written concerning this later in the report.

Overall, the stress-time histories "look good" taken by themselves, with the flatpacks (Fig. 11) considered separately from the HRSE (Fig. 12). An occasional gage is not consistent (e.g., #5002, #5022); however, overall a mean estimate can be constructed.

When looked at more closely, there arise major questions concerning the data when velocities and stresses are compared. Unfortunately, they appear to be unresolvable. These include:

a. The shape of the stress pulse is not consistent with that of the velocity. The stress gages rise abruptly to a peak, then fall, recover and level off at a plateau. Early-time closer matches in shape would be expected because of the one-dimensional analysis. Severe rate effects are implied in the data.

b. The rise to peak in stresses are much shorter than the velocity gages. Is this a true observation, or a reflection of gage geometry and inertial effects? Again, the data alone cannot resolve the issue.

c. At lower stresses, the elastic precursor, seen in all of the velocity records, is seen in some and absent in other stress records. None of the flatpacks appear to have one. The HRSE gages at 14.0 m do not contain one, and only three out of four at the 8.2-m range have it. This may imply that some seating of the stress gages is necessary before data are observed.

Although there are major inconsistencies in the data, this set represents one of the more complete sets with which to work. Many resources were spent in obtaining unusable data; however, each gage fielded pretest had an important reason behind it. On future tests some can be eliminated. In the final analysis, the data were good enough to address material properties questions of relevant interest at relevant stress levels. Unfortunately, the quality, although better than previous experience, was not good enough to resolve basic issues. The data were good enough to address questions concerning data validation, however, almost a first in the community.

DATA SUMMARIES FROM THE PARTICIPANTS

As explained, each analyst was given the data for his objectives. Basically, each one used the data presented in the previous section. Results varied considerably depending on the combinations used. Below are summaries copied directly from Quick Look reports. (The exception is AFWL/NMERI's, which was summarized by the author.) The participants basically fall into two groups--those that considered the velocity and stress data as being good (AFWL/NMERI, PACTECH and, to some extent, ARA) and those who use primarily the velocity data (ATI and CRT). This report will address the comparison between the two. The summaries follow.

a. AFWL/NMERI Summary (Ref. 24)

NMERI was tasked to put the velocity and stress waveforms (σ_{max} > 10 MPa) through the Lagrangian Analysis of Stress and Strain (LASS) (Ref. 13). The data consisted of both stress-time histories from the flatpacks and HRSE gages and the velocity-time histories. These were used to fit a least-squares stress or velocity, time, and range surface through the data, from which stress versus strain estimates were directly obtained from inversion of Equations 1-3. Basically, the stress came from the stress gages and the strain and strain differences came from the velocity traces. Figure 16 shows the resulting estimates. The three sets came about by using slightly different times of arrivals for combining the data. Figure 16b is for the data as recorded; 16c was made by arbitrarily making $1/2\sigma_{max}$ and $1/2V_{max}$ arrive at the same time; and 16a was made by making absolute TOAs agree.

When the stress versus strain curves are compared with Figure 4, the pretest estimate, it is seen that the data taken per se indicate strain rate effects. The soil appears to become quite stiff with initial loading, not allowing strains greater

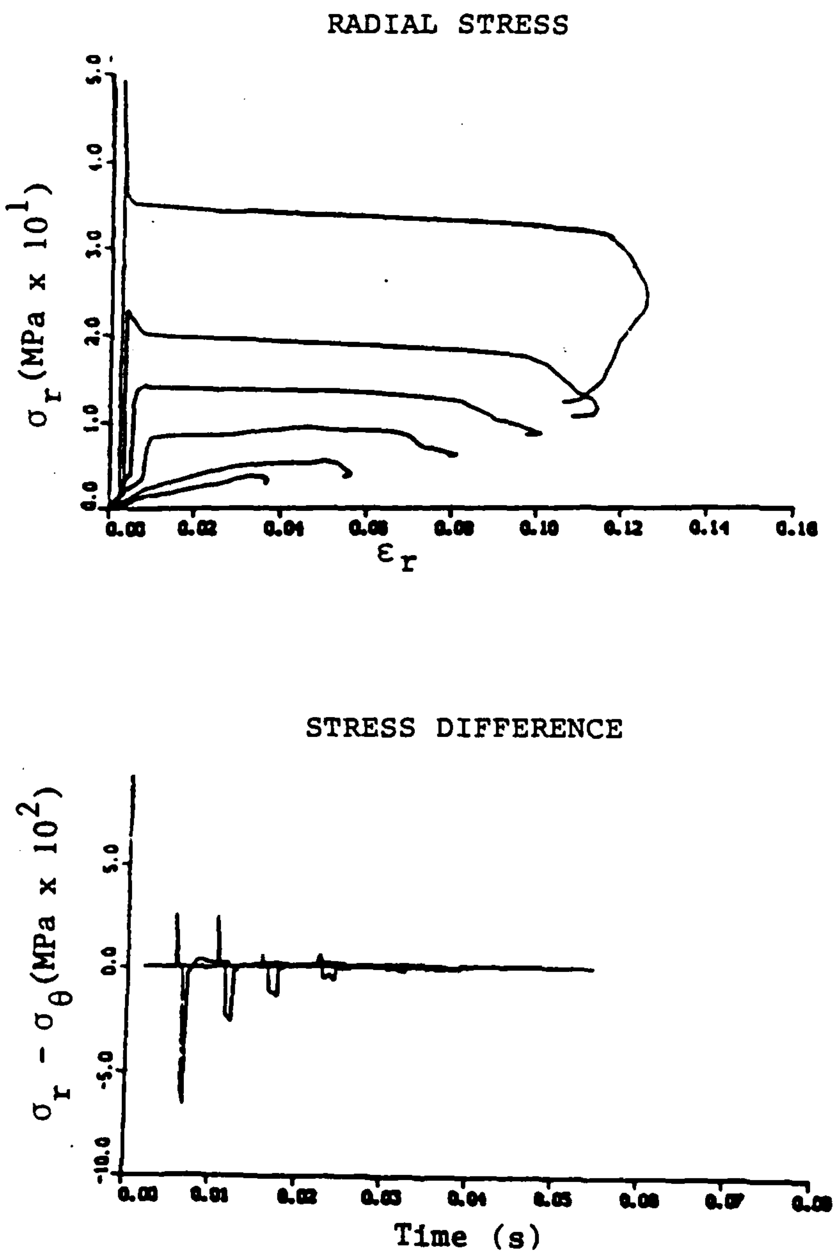
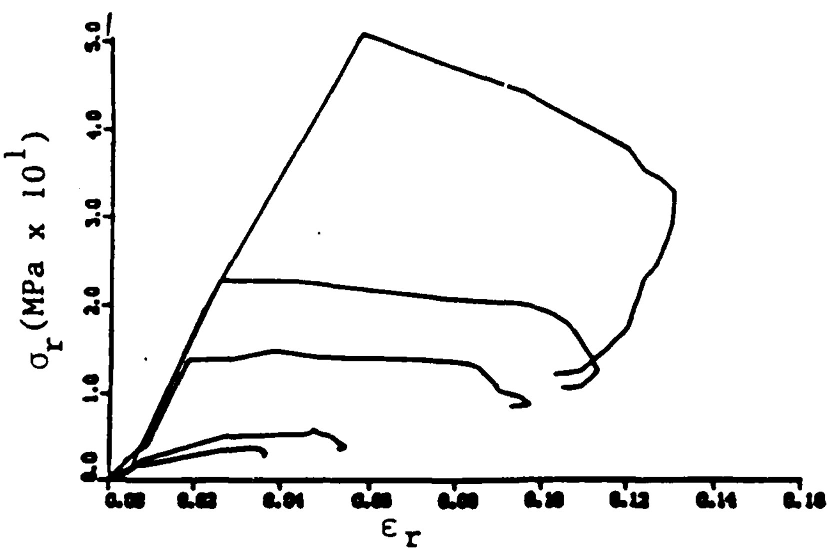


Figure 16a. Volumetric strain versus radial stress from LASS analysis (Ref. 22)

RADIAL STRESS



STRESS DIFFERENCE

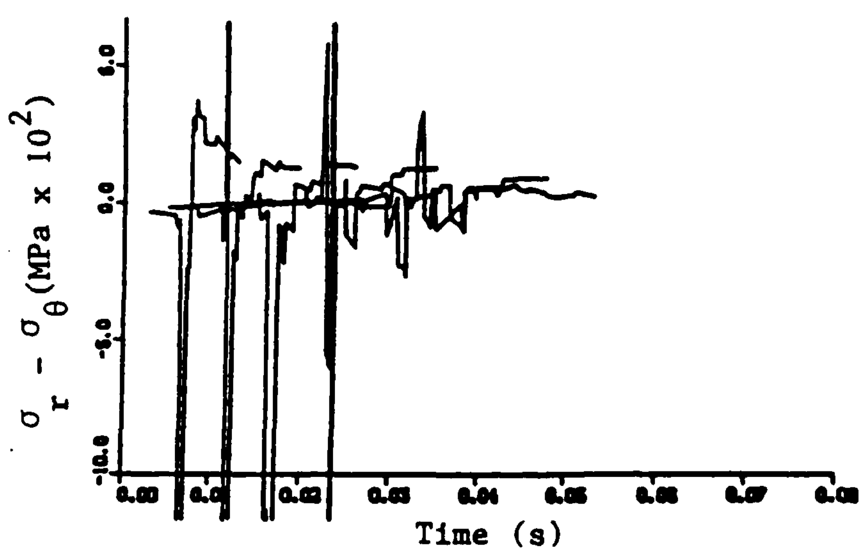


Figure 16b. <u>Volumetric strain versus radial stress from LASS analysis (Ref. 22)</u>

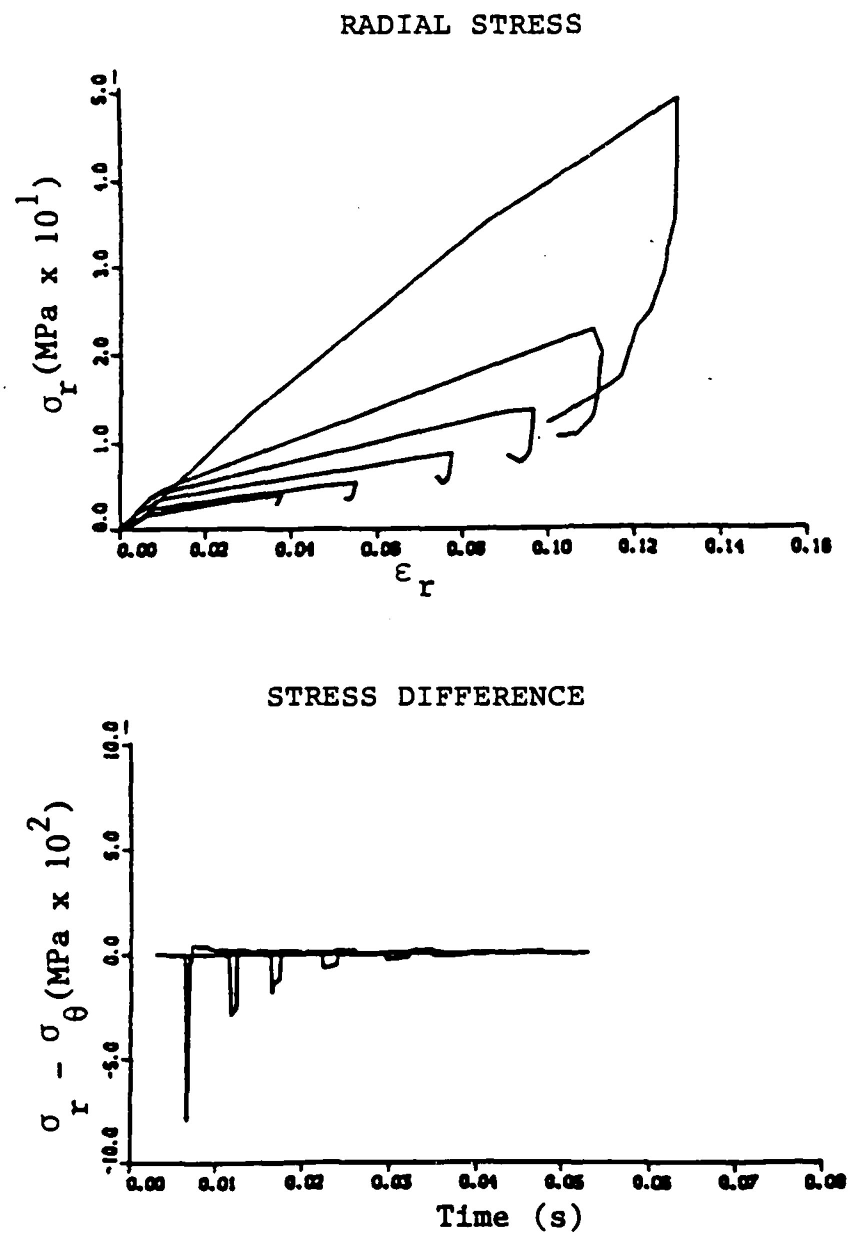


Figure 16c. Volumetric strain versus radial stress from LASS analysis (Ref. 22)

than 6% until after peak stresses are reached. It was concluded that the estimates were entirely dependent on arrival and rise times. Early-time estimates of stress differences also were dependent on rise times and are suggested to be incorrect. However, late-time estimates were dependent on data with small time derivatives and are more accurate.

b. ARA Summary (Ref. 25)

"A material model was developed from 1-D studies. This model adequately described the peaks and waveforms down to a stress level of approximately 5MPa as measured in the MP2 experiment. This model is between the laboratory model and the field estimate from Reference 7. The evaluation of the empirical pretest predictions against the MP2 data showed that predicted peak velocities were underpredicted by a factor of two. The attenuation rate of the velocity was predicted accurately. Peak displacements appear to have been generally underpredicted. Corrected data is necessary before this underprediction can be verified. The predicted attenuation rate for peak displacements appears to be too low. Accelerations were underpredicted at ranges less than 10m and accurately predicted at ranges greater than 10m. Measured accelerations appear to attenuate at a faster rate than predicted. The peak stresses were predicted within the scatter of the data. Stress data from MP2 attenuated at a faster rate than the prediction. The comparison of the redundant measurements indicates that the measurement set, as a whole is fairly consistent. It is also apparent that the instrumented test bed is fairly uniform within the Yuma material three layer (i.e., 15-75 m below the ground surface). Finally, MP1 and MP2 data appears to be consistent with the contained (nuclear and HE) data base."

c. ATI Summary

"The main task of event MP2 was to measure stress-strain curves, in situ, during an actual explosion.[1-3] Since stress gages cannot be relied upon to report free-field stress,[4] their accuracy had to be assessed as part of the main task. The resulting bootstrap operation succeeded: For the nearly spherical MP2 field, radial stress was found as a function of strain, in situ,[5] on strain paths of a type that occurs widely in surface-burst fields.[6]

"The shot's goals were much advanced by a method for extracting, from measured radial motion, rigorous upper and lower bounds on radial stress.[7] The method, itself a major result of the program, applies to uniaxial, cylindrical-radial and spherical fields. The bounds it furnishes are almost identical early in a pulse's unfolding, but they spread with time; still, through decay to less than half of peak amplitude, the gap between them proved narrow enough to disclose some likely errors in a stress-gauge output,[8] as well as unexpected material behavior (below). In a second theoretical but practical development, a way was found to choose optimum directions for gauge-lines.[9]

"Other MP2 results of note include these: a) Deducing hoop stress from measured radial stress and motion was shown by stress-bound analysis to be infeasible (at least for dry porous soils); hoop stress must be measured, whereupon radial stress can be found accurately from measured motion.[10] b) In Yuma alluvium, radial-stress pulses with amplitudes of ~1kb are determined almost entirely by motion. Indeed, they follow with useful accuracy from curves of peak radial velocity and arrival time versus slant range;[11] beyond that, it takes little motion-gage accuracy to determine them - and, for model-validation purposes, they add almost nothing to measured motion.

"In addition, below ~1/3kb, the model in widest use gave peak radial stresses, pre-shot, that fell with slant range at a considerable lower rate than in the shot itself (by ~.6 in power-law exponent).[12] Shear-enhanced compaction at peak stresses of ~1kb (in broad conflict with models) came as more of a surprise; though data-scatter makes that process only probable in MP2,[13] it now stands as a focus of concern over modeling methods. Forcible too is the finding that MP2's velocity pulses had long rise times from a system standpoint, when simply scaled to megaton yields.[14,15]

"Results like those obtained from event MP2 fill a basic need in developing stress gages, sample-and-lab-test procedures, and material models. True, it will take improved data-return to settle the question of shear-enhanced compaction, but records from recent experiments (Pre-MILL YARD 8, MILL YARD) suggest that adequate data can be had. If so, then events like MP2 can provide solutions to some ranking geomechanical problems, including i) better definition of volume changes due to explosively induced shear, ii) full experimental determination of stress in the direct (spherical) regimes of near-surface bursts, and iii) clear cut testing of the models' stress-strain relations in such key aspects as the accuracy of their shear stresses on spherical strain paths.

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12. Ref. 11, 33rd page.

13. Letter of 11 July 1985 to Cliff McFarland of the Defense Nuclear Agency from Jack Trulio, and enclosed documents ["Comments on an 'MP2 Analysis Review' by S. Peyton, dated 5 June 1985,", "Comments on a 'Statistical Analysis of Peak Velocities' by Dick Crawford (R&D Associates)," and "Comments on Some 'MP-2 Post-dictions' of R.T. Allen (Pacifica Technology)," by J. Trulio and J. Workman].

14. J. Trulio, "Comparison of Motions, Strain Paths and Stress Bounds from SRI Lab Shots and Event MP2," p. 117, 118 & 128, Minutes of the Eighth Meeting of the DNA Ad Hoc Cratering Working Group, Volume II: 20 February 1985 (March 1985; prepared by Jean Radler of RDA Logicon).

15. N. Perl, J. Workman and J. Trulio, "Strain-Path and Stress-Bounds from Laboratory Tests," p. 2, 43, 44 & 61, Applied Theory, Inc. Technical Report No. ATR-85-66-2, 1 October 1985 (Final report for Contract No. DNA001-85-C-0026)."

d. CRT Summary (Ref. 18)

"Based on the results presented herein, the MP2 test appears to have met most of the objectives. Both pre- and post-shot calculations agree with the experimental data set within acceptable error bounds, although the post-shot results are clearly a better overall match. The improved post-shot comparison was a direct result of more careful modeling of newer laboratory data, rather than an arbitrary adjustment of the fit simply to match the test. These comparisons, therefore, suggest that the current standard material properties test procedures are adequate to provide the data needed for constitutive models of material behavior under simple, dynamic, load-unload conditions. In addition, using the "best-fit" post-shot material model in a recalculation of the NSS event produced a crater size and shape similar to that of the experiment, a significant improvement relative to the pre-shot calculation.

"While comparisons of calculations with this shot lends credibility to the current modeling techniques, the MP2 test, by itself, did not provide any significantly new data about material properties of Yuma alluvium that were not obtainable by other less expensive or more pertinent techniques. Furthermore, the sphericity of such an experiment limits the load-unload paths exercised to those readily obtainable in the lab and requires the charge be placed at a depth which is not as pertinent as the near surface media. Simpler in-situ tests, such as CIST or HEST could provide such near surface data at lower cost or risk. However, the apparent spread in the data and problems in obtaining complete stress or velocity-time histories probably preclude using any of these tests to generate constitutive relations. Rather, such experiments should best be used, as in our study, to check the material parameters derived from lab tests and simple field explorations (i.e., seismic logging, and in-situ density and porosity measurements)."

e. PACTECH Summary (Ref. 21)

"Conclusions. The ideas behind the Lagrangian analysis of velocity data are presented in Section 2. The basic assumptions are listed and the sensitivity of the results to these assumptions are explored. This technique was applied to the velocity data generated by the MP2 event and a small scale experiment performed by SRI. The extracted stress and strain histories were also used to evaluate the degree to which calculations agreed with experiment.

"The Lagrangian analysis technique is useful for deducing the consistency of a set of measured velocity and stress data. The deduced strain paths are quite sensitive to the exact nature of the velocity field. This sensitivity is a two-edged sword. It provides the means to put a sharp contrast on comparisons between experiment and theory. Unfortunately, this same sensitivity amplifies the errors and uncertainties in the data used to construct the strain path.

"Comparisons of the strain paths extracted from MP2 and SRI showed a qualitative difference in the observed motion in these two experiments. The motion in MP2 was more nearly a pure shock than the motion at the small scale. Whether this difference is due to scale, sample preparation or overburden remains to be determined.

"Both MP2 and the SRI experiments showed some additional volumetric compression during the unload phase of the motion. The MP2 result is more suspect, since two different reasonable fits to the velocity data produced markedly different results. Given the extreme sensitivity of the volumetric strain computation, it is not clear whether, in actual fact, such behavior did take place.

"The comparison of the extracted stress and strain histories with PacTech's post-test model was shown. Rather good agreement was obtained with one of the two MP2 fits at the 5.22m station. This lends further support for the idea that response of the material in MP2 was conventional. The remaining stations imply that the numerical model displayed a stiffer response than the material. Our model is also stiffer than the WES recommended properties as shown in Section 3.

"The major controversial point raised in this analysis was the nature of volumetric strain after the arrival of peak stress. Depending on the fit chosen for MP2, there was either 4%, or less than 0.5% additional compression during the unload phase of the motion. The SRI data, which is a bit higher quality set, also showed some compression during unload. The magnitude, though, was less than 2%.

"The volumetric strain is the sum of the hoop and radial strain. These strains have opposite signs so that the volumetric strain is the difference of two large numbers. The volumetric strain is, therefore, particularly sensitive to various fits used in the analysis. Given this sensitivity, it is very difficult to attach much significance to the volumetric compression seen after peak stress passage.

"Based on the data presented here, it is certainly not the time to discard conventional models. The comparison between the numerical solution and the extracted stress and strain histories shown in Figure 16 points out the degree to which conventional models can match at least one interpretation of the MP2 data.

"The SRI data may indeed require the use of unconventional models. A strain rate dependent model such as the standard linear solid would produce the additional compression during unload. Such a model was used in our pre-shot predictions and may have been abandoned prematurely.

"The underlying question that is being raised here is how to judge the extent to which calculation and experiment agree. The usual approach has been to compare velocity and stress-time histories and note the differences. Unfortunately, the measurements contain unquantified errors and it is always tempting to ascribe any difference to experimental error. The Lagrangian analysis provides a means to double check the quality of the experimental data. Using the velocity histories, bounds can be developed on the radial stress and the consistency of the data can be established.

"The Lagrangian technique is not without its own drawbacks. It is subject to error introduced in the attempt to construct the velocity field based on measurements at a few points. As shown in Section 2, rather similar velocity fields can have very different strain paths associated with them. It is quite easy, as was shown with the MP2 data, to generate considerable differences in the strain histories by choosing slightly different fits to the data. Comparing calculated and extracted strain paths is certainly a more sensitive test of the calculation; however, the strain path data are likely to be less reliable than the velocity histories from which they came.

"Trulio has suggested applying the extracted strain path to a numerical model and comparing the resulting radial stress with the stress bounds. Such a comparison is certainly the most severe test of a numerical model. If the strain path were error free, such a procedure would be very useful. The moduli of most materials are sufficiently large, however, that small changes in the strain lead to rather large changes in the computed stress.

Using these moduli to leverage any error in the strain path is likely to be more misleading than useful.

"In conclusion, given an appreciation of the uncertainties inherent in the method, the Lagrangian analysis presented here provides a useful tool to check the consistency of experimental measurements and to evaluate the extent to which calculations and experiment agree.

"Recommendations. In our opinion, MP2 achieved most of its objectives, was a success and should not be repeated. We strongly recommend additional spherical testing at both the laboratory and field scale. The field scale testing can be done with charges ranging from a few hundred pounds to, at most, one ton. The minimum charge size is dictated by the physical size of the gage packages employed. Our particular preference is for more events with fewer gages per event. (This is opposite of current practice, except for special "add-in" tests such as Pre-CARES 2 and 3.) Loading too many gages on a single event overloads the field crews. Wires are hooked up wrong and power supplies are saturated--entire gage arrays are lost.

"Since one of the long-term objectives of in-situ testing is to explore previously untested locations that very likely lack site test support facilities, one might define the test size as what can be carried in on two or three trucks. Another approach would be to define a "cost per test," with a schedule of something like a dozen events for absorption of equipment acquisition costs. The costs for the last few CIST events could be used as the point of departure.

"The strain path analyses presented in Section 2 would have had a much stronger influence on our material model development if they had been conducted in parallel with our MP2 post-test studies rather than later in time. We plan to integrate this technique into our model development program when there are sufficient, redundant velocity data to justify its use. The model, for some flow fields, provides relatively tight bounds on radial stress. Thus, the objective of providing an independent check of radial stress gages can be achieved (for these flows). The more critical objective of providing in-situ, dynamic material properties is considerably harder to obtain. The reader can examine Figures 5 and 6, for example, and see for himself whether these bounds on the hydrostatic "crush curve" are useful or not. There is clearly room for improvement in our current model as shown by Figures 17 and 18.

"Finally, a debate has waxed and waned through several letters between ATI and PacTech concerning the support for shear-induced compaction that can be derived solely on the basis of the MP2 data. Our position is documented in Section 2 and the appendix in more detail than the average reader can tolerate. Both fits have statistical credibility. The ATI fit, however, leads to a physically unreasonable result, namely, total compaction of 40% (see Figure 7, Reference 3) well in excess of the nominal values for the site (17 to 23%). Our final salvo (at this stage in the battle) is that statistical purity should yield to physical reality in a physics program."

In addition to the summaries, two letters were sent concerning the analysis by ATI and CRT. Many of the arguments sum up the results of the test, and they are included in Appendix A.

Several important conclusions may be drawn:

a. Concerning the data itself. The data recorded for the radial stress and velocities was one of the better sets. Reproducible (but not validated) traces were obtained for $V \leq 80$ m/s and $\sigma \leq 1$ GPa. Each "looked good;" however, upon detailed analysis they were inconsistent with each other, especially with regard to rise times and peaks. The state of the art in instrumentation was achieved as we know it and the data allowed a detailed analysis as to its validity.

b. When stress and velocity gages are both used in a single analysis, rate effects (strain hardening) are required in the model. Because this deals directly with the rise times, which were not validated, it is very uncertain if this is a real effect. This question will be taken up in greater detail.

c. If the experiment is calculated directly from laboratory estimates "corrected for the in-situ effect," the results are within the test data scatter if velocity pulses are compared (again the stress data would require strain rate effects). This may lead us to the conclusion that we presently know enough about dry alluvium to predict its behavior directly from lab results and further field tests are not required. This should not be taken as being opposed to all in situ testing because wet-layered and rock sites have not been addressed.

d. Shear compaction was postulated by ATI based on the data, but it is very dependent upon the release portion of the velocity pulse. This portion, although measured better here than in other tests, contains a good deal of uncertainty. Substantial improvement must be obtained for velocity and stress measuring if this type of test is to be repeated for measuring this phenomenon.

e. The test data were within the error bounds for dry alluvium sites. It adds nothing new to the empirical database.

Overall, the test was a success in that a state-of-the-art set of data was obtained. It led to questioning of modeling techniques. Unfortunately, answering all questions precisely cannot be done with the data. Many improvements must be made in data gathering before the modeling questions can be completely addressed. Before the improvements are made, further testing of this type in dry alluvium is not encouraged. This is not to say that testing in other media would not be important.

ERROR ANALYSIS

OBJECTIVE

This is a new analysis, not contained in the previous summary, to attempt to answer two of the outstanding questions: (1) are the stress and velocity gages compatible, and (2) what are some of the magnitudes of errors present in the data (or what type of errors can be expected in the future)?

Important information can be obtained from simple, careful analysis. In this case strain paths show that, especially at ranges less than 10 m, the flow field is in uniaxial strain (i.e., one-dimensional). This analysis makes that assumption and calculates material models using it.

The other question is an attempt in understanding what error will be associated with a prediction. Instrumentation error immediately comes to mind; however, more fundamentally, is there a limit which nature places on us which can never be bettered?

ONE-DIMENSIONAL ANALYSIS

Figure 8 shows that, upon initial loading, spherical tests are basically one-dimensional in uniaxial strain-stress space. This rather simple result allows calculation of stress and strains from either stresses, velocities or a combination of the two with (Refs. 26 and 27)

$$\sigma = \rho_o c v \tag{12}$$

$$\sigma = \sum_i \rho_o c_i \Delta v \tag{13}$$

$$v = \sum_i \frac{\Delta\sigma}{\rho c_i} \tag{14}$$

$$\varepsilon = \sum_i \frac{\Delta v_i}{c_i} \tag{15}$$

$$\varepsilon = \sum_i \frac{\Delta \sigma_i}{\rho_o c_i^2} \tag{16}$$

where

σ = peak stress

p_o = 1900 kg/m^3

v = peak particle velocity

c = propagation velocity

ε = peak strain

If the loading curve can be considered so that loading takes place on a linear path, either linear elastic, or in this case a Rayleigh line to peak stress, a stress and strain estimate for a particular stress can be calculated simply from (12) above and

$$\varepsilon = \frac{V}{c} = \frac{\sigma}{\rho_o c^2} \tag{17}$$

The stress and velocity peaks can be obtained from the peak stress/velocity versus range curve and c, the propagation velocity, may be calculated from the TOA versus range curve.

For this analysis, all ranges are taken with respect to the edge of the sphere (R = 1.5 m). The first step was to construct an estimate of arrival times of the main shock with respect to range. Times are plotted in Figure 17 for only the data at less than a range of 5.0-m radius (the higher pressure data). Both times from the velocity and stress gages are used. Three fits were tried: (1) linear, (2) quadratic with zero intercept, and (3) cubic. Since we are in the high pressure region, the curve was not expected to be linear; however, it does give a best average as

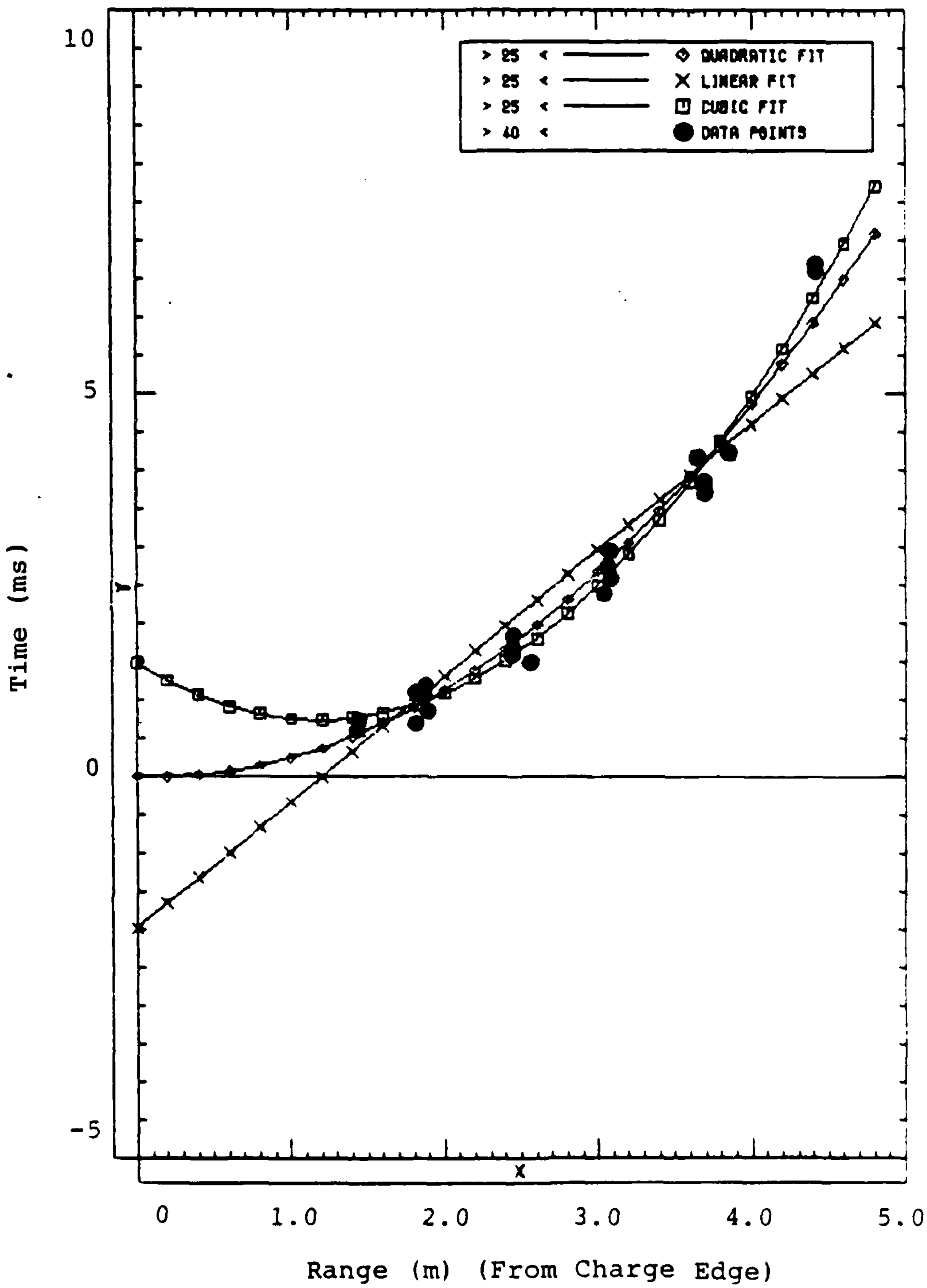


Figure 17. Time of arrival of main shock with respect to range

$$TOA = -1.98 + 1.64R \text{ (ms)} \tag{18}$$

Cubic equations tend not to be accurate predictors outside of the data. Because of this, the best fit included negative velocities. The average errors were not much better than the quadratic fit which gives TOAs of

$$TOA = 0.089R + 0.32R^2 \text{ (ms)} \tag{19}$$

as a best estimate. This implies that the propagation velocity at any particular range is given by

$$c = \frac{dR}{dT} = \frac{1}{(0.089 + 0.64R) \times 10^{-3}} \text{ (m/s)} \tag{20}$$

Based on the analysis of MP3 (Ref. 2), the velocity data were considered reliable at the closest-in range (however, a comparison of it with respect to the stress data is given below). As already discussed, the velocity peak data will not support a single, linear fit through the entire range. The data were, as with the TOA data, limited to $3.9 < R < 6.5$ m (from the edge of the sphere). A best fit to this data (Fig. 18) gave

$$V = 170R^{-1.0} \tag{21}$$

Similar analysis was done to the flatpack stress data (Fig. 19) giving

$$\sigma = 1.9 \times 10^3 R^{-2.19} \tag{22}$$

Using the TOA estimate and the stress estimate, peak velocities were calculated and are shown in Figure 18. They appear to be a factor of 2 higher than the measured velocities. A factor of 2 would also be seen calculating stresses, making stresses calculated from velocities appear to be a factor of 2 lower than measured.

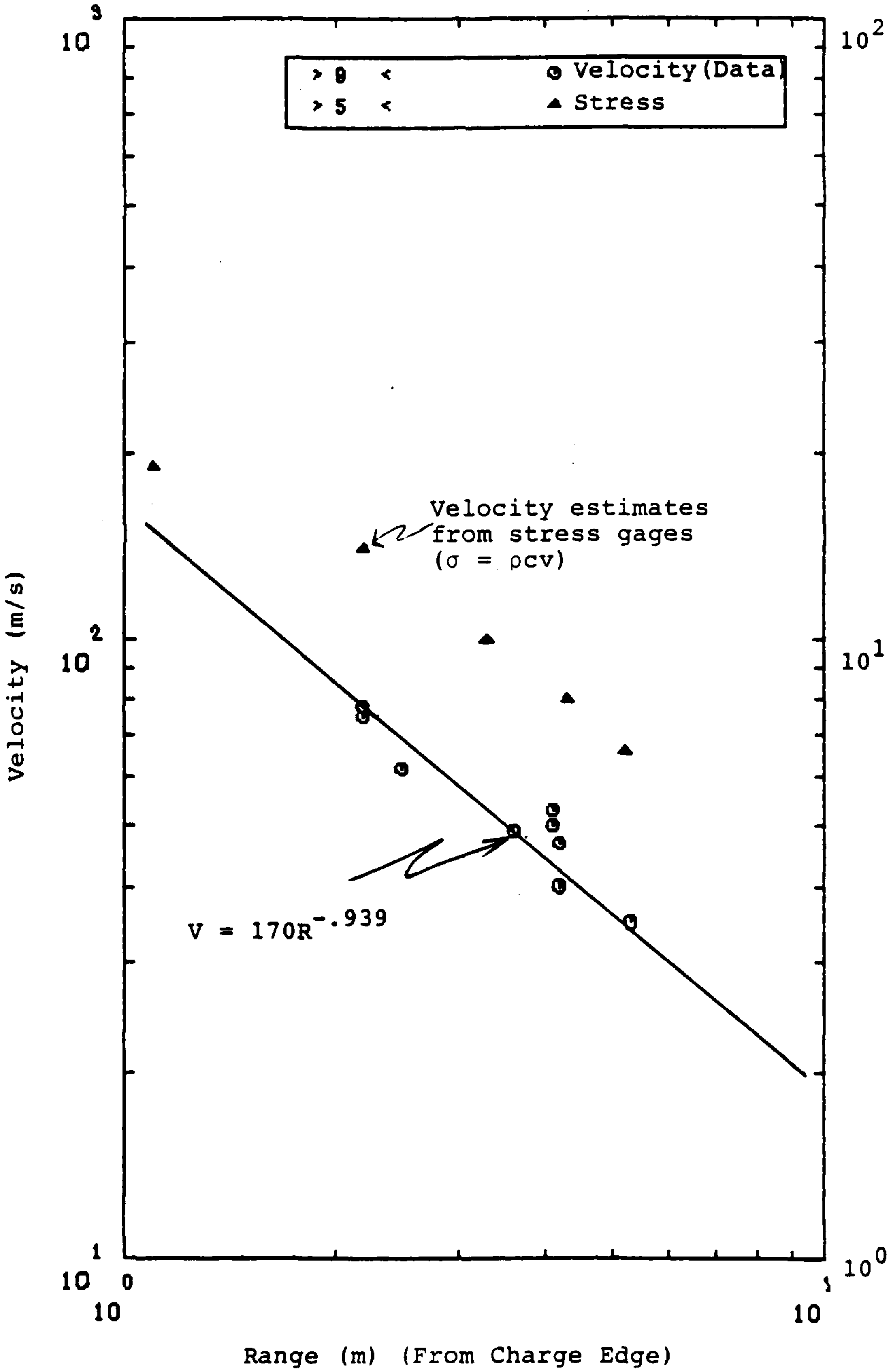


Figure 18. Peak velocity with respect to range (from both velocity and stress gages)

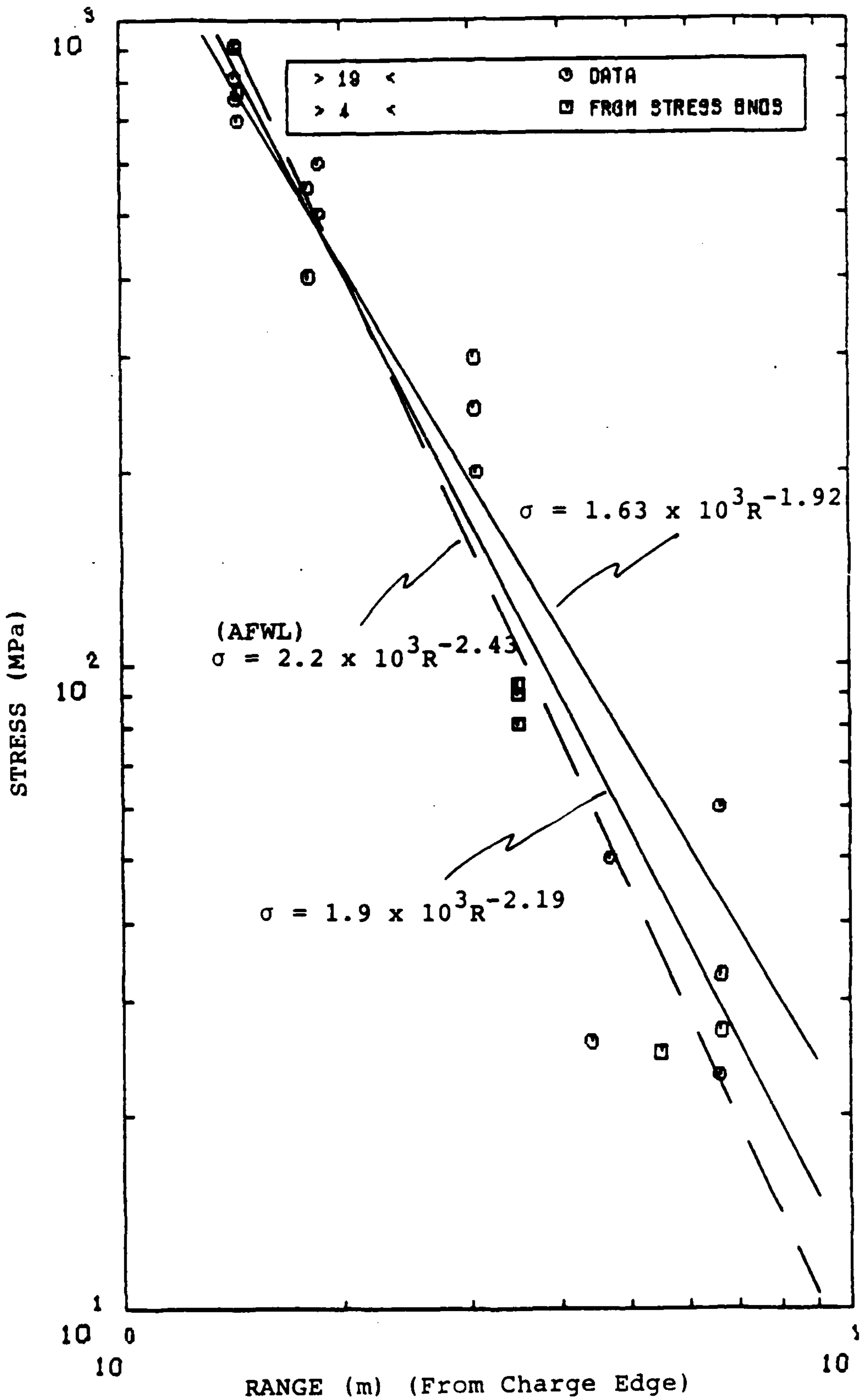


Figure 19. Peak stress gages and stress bounds with respect to range

Strains were calculated next. Since this is a one-dimensional calculation, again a choice is possible--either use stress or velocity or both. Initially, velocity was considered the best parameter and its results are seen in Figure 20, with a variety of other data. The circled crosses are results from velocities being used to calculate both stresses and strains. The WES lab data and best estimate for in situ are also given (Ref. 7). These data appear a bit stiffer than those in Reference 7; however, one point from Reference 28 helps substantiate the TOA data. Several points from Reference 29, the CDC-1 planar test, also give confirmation of the low stress curve.

In summary, the velocity data and TOA data appear to give a result that agrees with the WES data. The WES data were used to calculate the event (Ref. 18), with good accuracy in velocity.

Now different combinations were used to calculate the stress versus strain curve (Fig. 21). The key in the upper right-hand corner indicates what was used to calculate what. The first notation indicates what was used to calculate strain; the second notation indicates what was used to calculate stress. When velocities used to calculate strains and stresses are used directly, the results show a little steeper curve--not out of reason. When stresses are used to estimate both stresses and strains, strains on the order of 40% are indicated. Simple physical arguments of conservation of mass prohibited this amount of strain.

This analysis suggests that measured stresses are higher (approximately by a factor of 2) than physically allowed.

Another interesting comparison can be made through extrapolating what a velocity pulse might look like when extrapolated to a flatpack range. Figure 22 presents a mean stress record for the 3.5-m range. Also included is a single

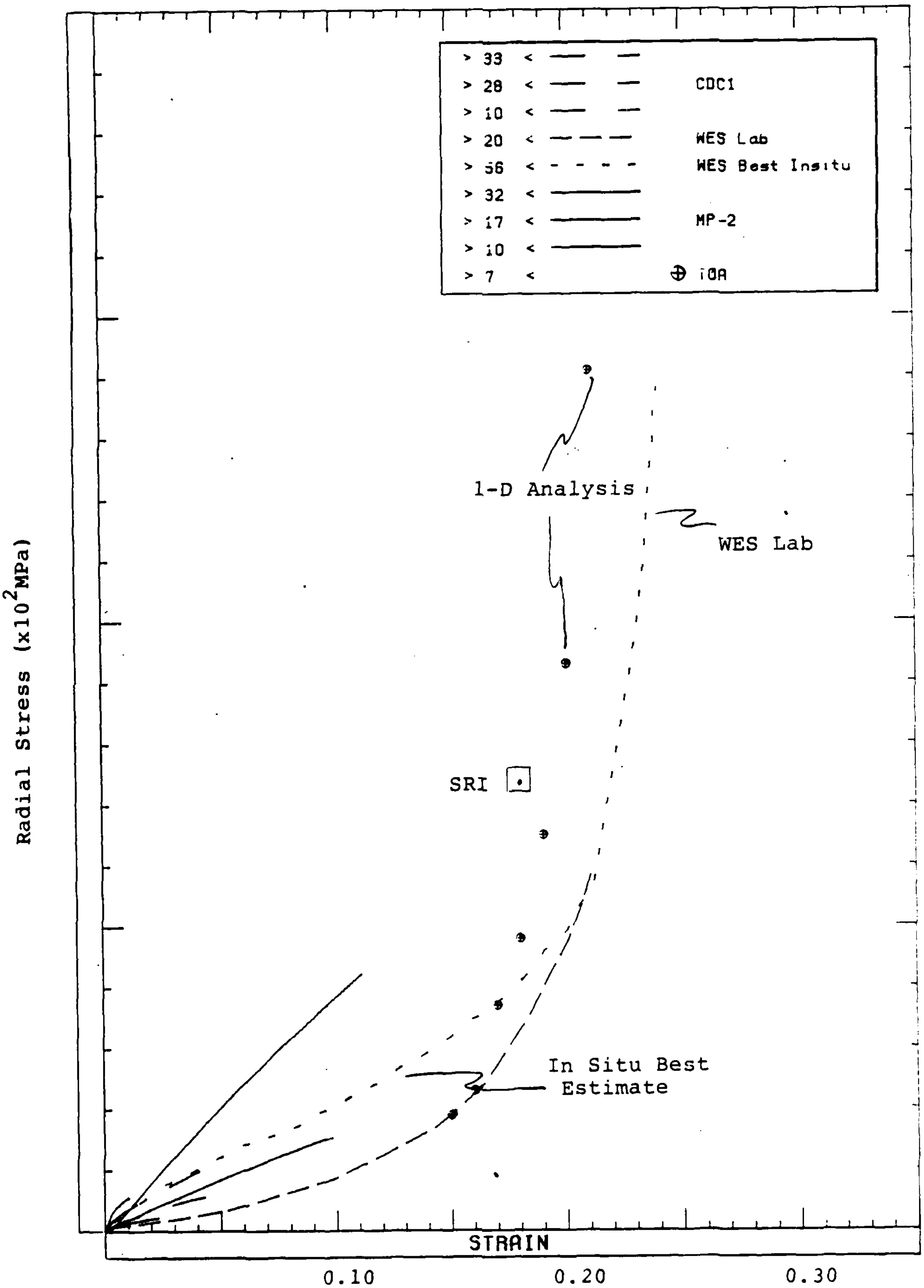


Figure 20. Uniaxial strain versus stress from velocity data

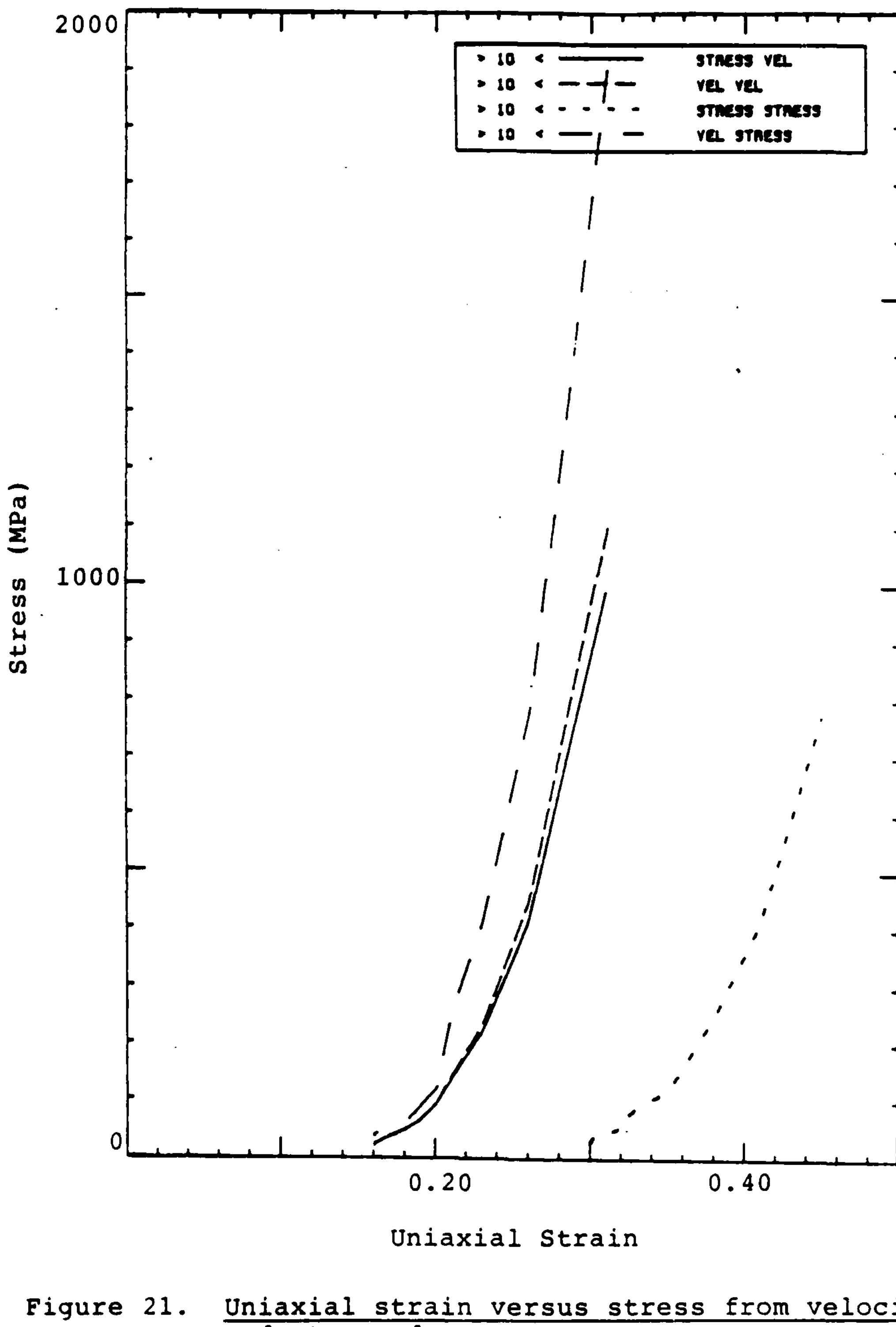


Figure 21. Uniaxial strain versus stress from velocity and stress data

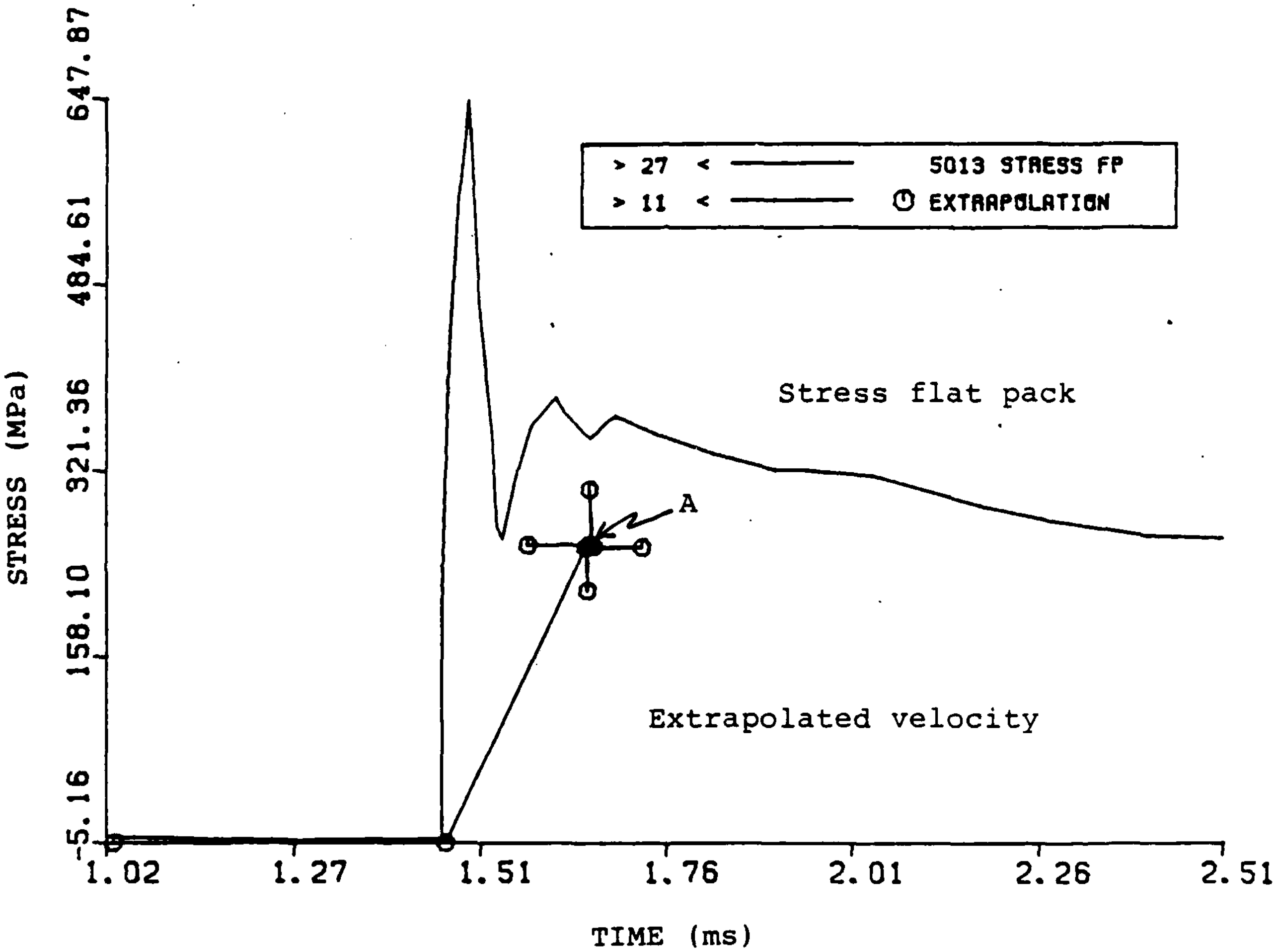


Figure 22. Comparison of radial stress and extrapolated velocity waveforms

line ending in a point with error bars. This represents the TOA, rise time and peak stress, as seen from the velocity data. The error bars are derived from the velocity data.

Based on the velocity data, the rise time and peak stress appear to be inconsistent. The local maximum labeled point A in the stress record appears to be more realistic. The first sharp peak in stress could be explained as inertial effects of the gage. Some simple one-dimensional calculations help prove this hypothesis. If the stress record is real, then strain rate effects in alluvium must be called upon to explain the differences. However, the data, as they are, will never be satisfactory.

Stress Gage Analysis

The apparent inconsistency in the stress gage and velocity derived stress results (shown in Fig. 22) is the overall inconsistency with the test. Whether or not strain rate effects are important in dry alluvium are resolved by answering this one question. Since the true magnitude of a quantity at a point is independent of the measuring system, the output of a gage must be evaluated properly to represent the correct value. Figure 22 indicates conflicting peak stress values at the same point from two different gages, the reasons for this are therefore of interest.

Two hypotheses can be considered in attempting to explain the differences in the gage records.

a. Strain rate effects in the alluvium may be significant.

b. Inertial effects in the stress gage may be significant.

Earlier in this MP2 report, material properties derived from stress gages only are not physically realizable because of the large strains. Considering this, the second hypothesis (i.e., inertial effects) has been assumed to be the dominant influence. An analysis using some simple one-dimensional calculations help prove that this effect is indeed important.

The stress gage and alluvium are represented by the idealized case of Figure 23. The boundary between the two materials is assumed to be cohesive and the stress is applied at normal incidence. The state of stress is a uniaxial strain condition resulting in a good approximation of the situation with planar 1-D. The partitioning of stress and velocity at the interface can be evaluated from equations given by Reference 26. Using the equations and the material properties given in Figure 23, the stress and velocity distributions at the first interface are given by

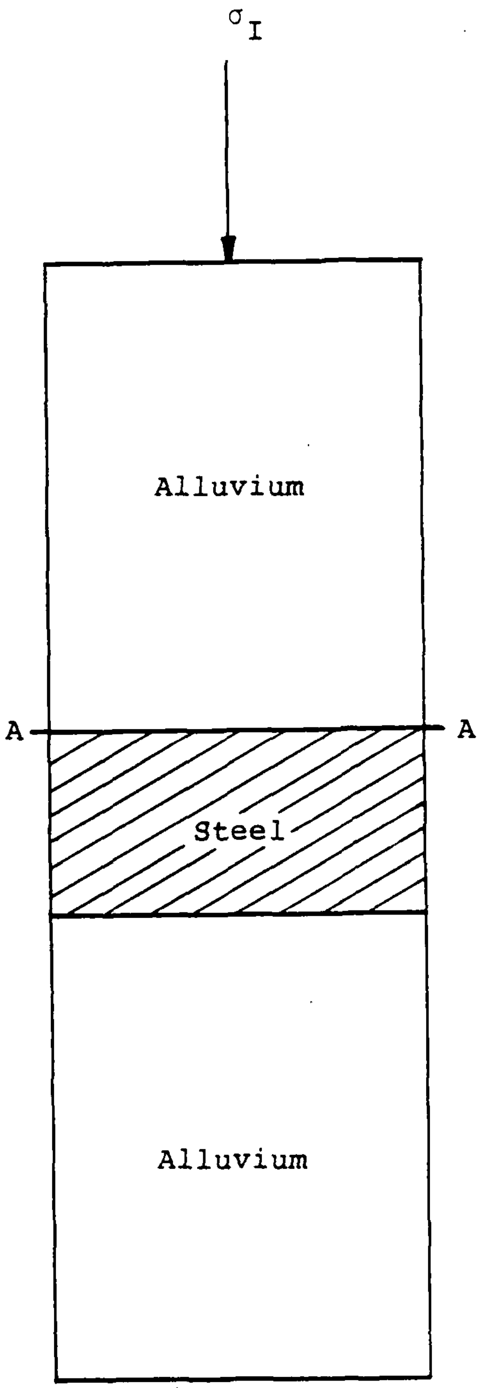
$$\sigma_T = 1.98\sigma_I \text{ MPa}$$

$$\sigma_R = 0.98\sigma_I \text{ MPa}$$

$$\left.\begin{aligned} V_T &= 4.4 \times 10^{-8}\sigma_I \text{ m/s} \\ V_R &= -1.7 \times 10^{-6}\sigma_I \text{ m/s} \end{aligned}\right\} \quad \sigma_I \text{ in Pa} \qquad (23)$$

where the incident, transmitted, and reflected values are denoted by the subscripts I, T, and R, respectively. The negative sign indicates a tensile wave.

These results indicate that the initial stress transmitted through the steel is approximately double that of the incident applied stress, while nearly all of the velocity is reflected back into the alluvium. It would seem at first glance that the sharp peak in two stress records (Fig. 22) could be caused by the doubling of transmitted stress at the interface, but this is not true. For a 0.0127-m (0.5-in) thick steel layer, representing the stress gage, the transit time across the steel for wave



<u>Alluvium</u>

ρ = 1900 kg/m^3
c = 300 m/s

<u>Steel</u>

ρ = 7800 kg/m^3
c = 5800 m/s

Figure 23. <u>One-dimensional idealization of a stress gage in alluvium</u>

propagation is on the order of 2 μs after which the stress wave will attenuate with time. This is too short a period of time over which to record data in the field and also is not readily captured in calculations. The sharp peak in the stress gage record of Figure 23 has a rise time of about 30 μs, which is substantially larger than the 2-μs transit time. These observations invalidate the argument of simple transmission theory to explain the difference between the stress gage record and the peak stress obtained from the velocity data.

A general elastic equation of motion is

$$\rho\frac{\partial^2 u}{\partial t^2} = (\lambda + G)\frac{\partial\bar{\varepsilon}}{\partial x} + G\nabla^2 u + F_B \tag{24}$$

where

λ, G = Lame's constants
$\dot{\varepsilon}$ = volumetric strain
ρ = density
∇ = gradient
u = displacement
F_B = body forces

In general, for a body in motion, body forces include the weight (gravity) and inertia of the object. Inertia of the stress gage coming up to speed with the surrounding soil appears to be a likely candidate. To estimate the inertia effect then, calculate

$$F_B = \sigma A = ma \tag{25}$$

$$\sigma A = (\rho)(\text{volume})\left(\frac{v}{t}\right) = \rho A T\frac{v}{t} \tag{26}$$

$$\sigma = \rho T\frac{v}{t} \tag{27}$$

where

σ = inertia stress

A = cross-sectional area of gage

T = thickness of gage

v = particle velocity

t = rise time

a = acceleration

m = mass

The particle velocity and rise time to be used are those associated with the peak velocity data in Figure 23. Substitution of the appropriate values gives the inertia stress as

$$\sigma = \frac{(7800)(0.0127)(302)}{0.00015} = 200 \text{ MPa} \tag{28}$$

The significance of this value is best illustrated by point A in Figure 24. If the "true" stress record is assumed to be given by the dashed line and the correct peak stress is given by point A, then the addition of the inertia stress to point A accounts for 91% of the sharp peak indicated by the stress gage.

An analysis was also performed using the CRALE 1-D planar code (Ref. 4) with a Speicher-Brode, 9.9-kbar surface burst loading to approximate the source. Two cases were examined--one for a layer of homogeneous alluvium and one for the same layer of alluvium with a 0.5-in zone of steel representing the stress gage. This was done to investigate the influence of the steel layer on the resultant stress and velocity-time histories.

Figures 25a and 25b show a comparison of the stress and velocity-time histories, respectively, for the two cases. In Figure 25a it can be seen that the presence of the steel layer has a significant influence on the peak stress value and has a rise time to peak on the order of about 20 μs. Figure 25b

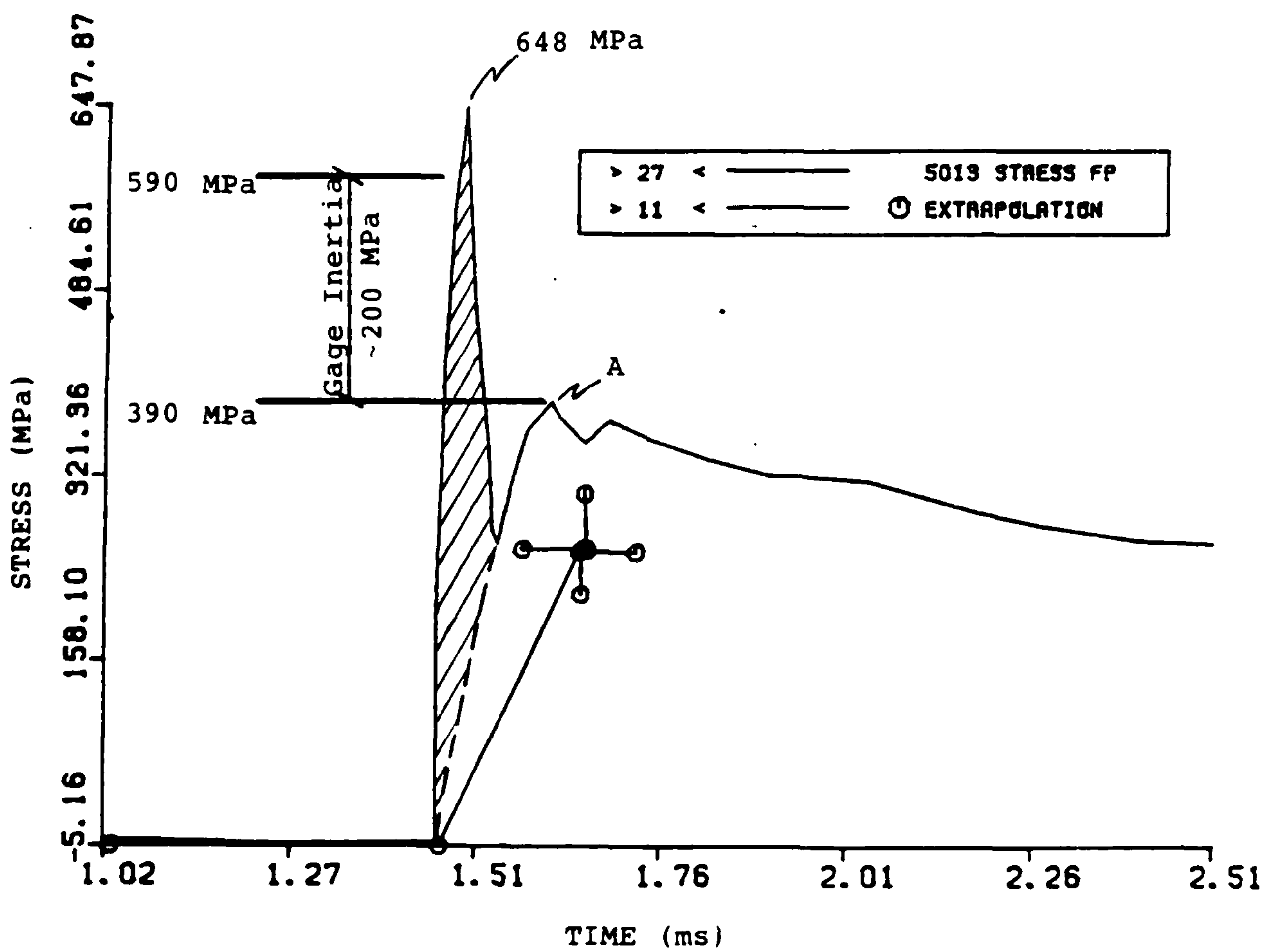


Figure 24. Comparison of radial stress and extrapolated velocity waveforms indicating effect of inertia on stress gage waveform peak

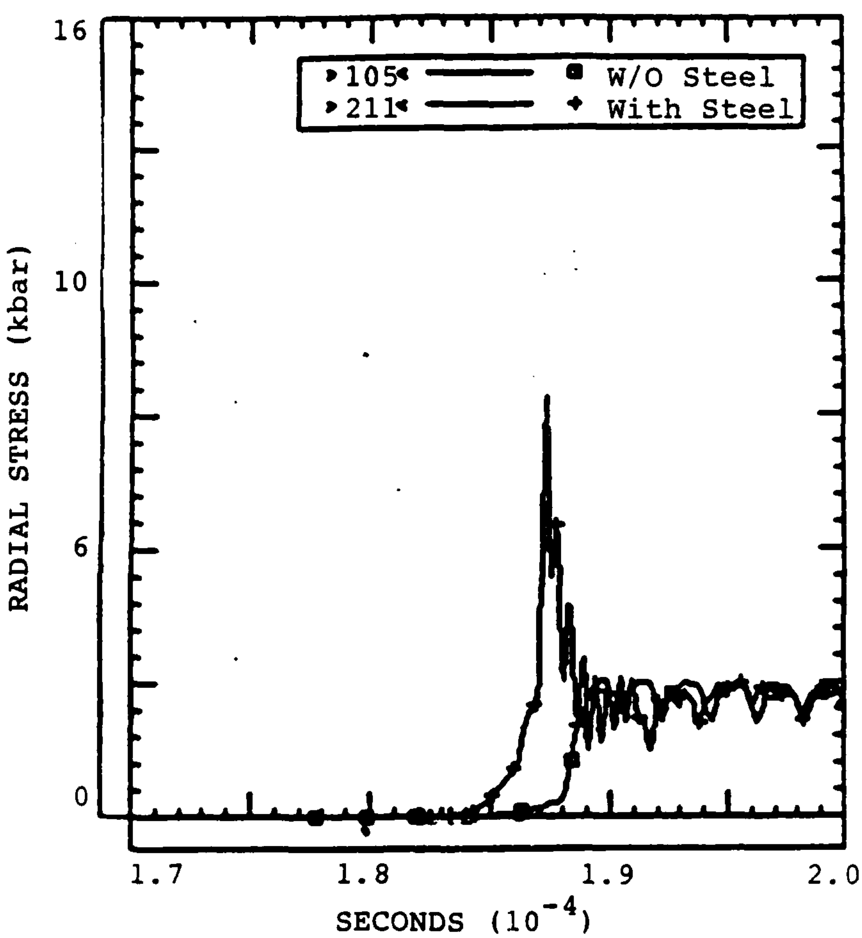


Figure 25a. Results of CRALE 1-D surface burst loading on alluvium and alluvium with idealized stress gage (Comparison of stress records with and without steel layer)

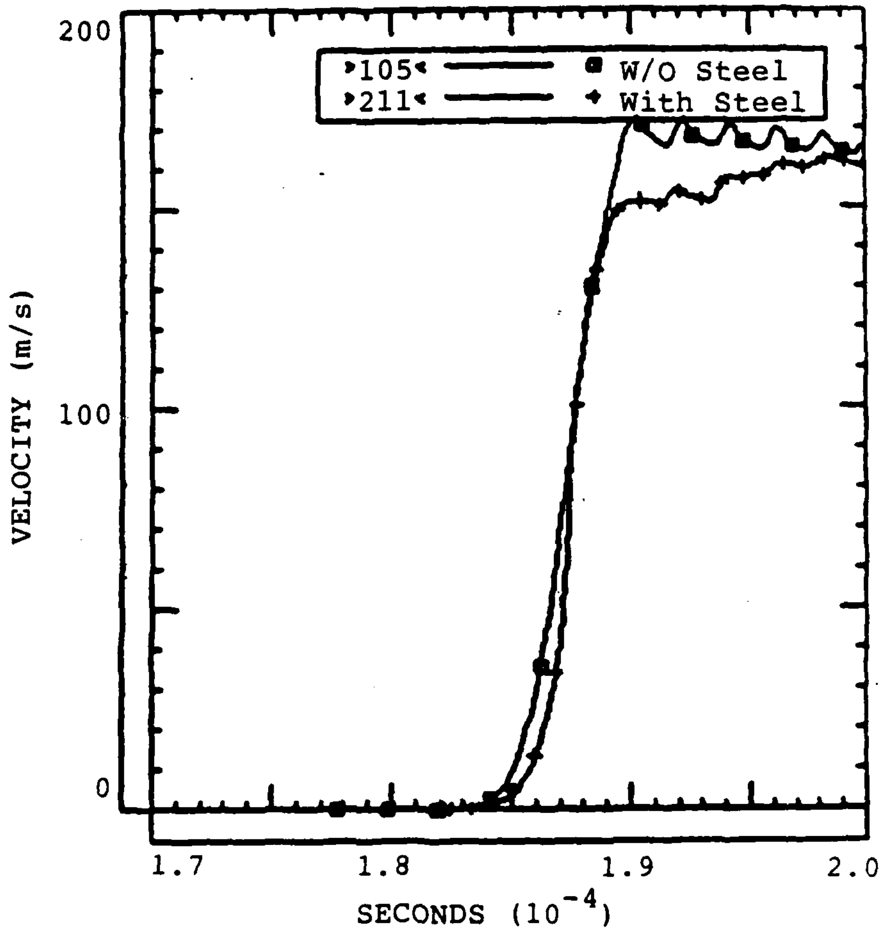


Figure 25b. Results of CRALE 1-D surface burst loading on alluvium and alluvium with idealized stress gage (Comparison of velocity records with and without steel layer)

indicates that the presence of the steel layer does not have a significant influence on the velocity profiles.

Using the code-generated time histories, one other comparison of interest was obtained. A stress-time history was constructed from the velocity profile for the case with the steel layer, using the relationship, $\sigma = \rho c V$. Figure 25c compares this result with the stress-time history from the code. The important difference between the two curves is the lack of a sharp peak on the velocity derived record. This result is in good agreement with the proposed hypothesis and the behavior observed in the data shown in Figure 22. This, then, leads to the important conclusion that inertia effects are significant in the response of stress gages in the field. The one-dimensional analysis performed supports this conclusion, assuming that strain rate effects in the alluvium are not significant.

ERROR ANALYSIS

Two simple error analyses were done to provide insight into (1) what is necessary for accurate velocity measurements, and (2) how accurate one can expect to be.

A critical area of uncertainty when interpreting field data records is in the possible error introduced into the measurements with baseline shifting of later time velocity measurements. Since it is often necessary to adjust field records to account for such things as apparent baseline shifts, it is important to know how this will affect the final results. The sources of error can be complex and difficult to define individually. Even certain assumptions can be sources of error, but often they are required in order to make the data analysis tractable. In general, corrections involve the adjustment of data which may include several possible sources of error. This in effect provides a modification which may cover the combined effects of several errors that can significantly influence the data.

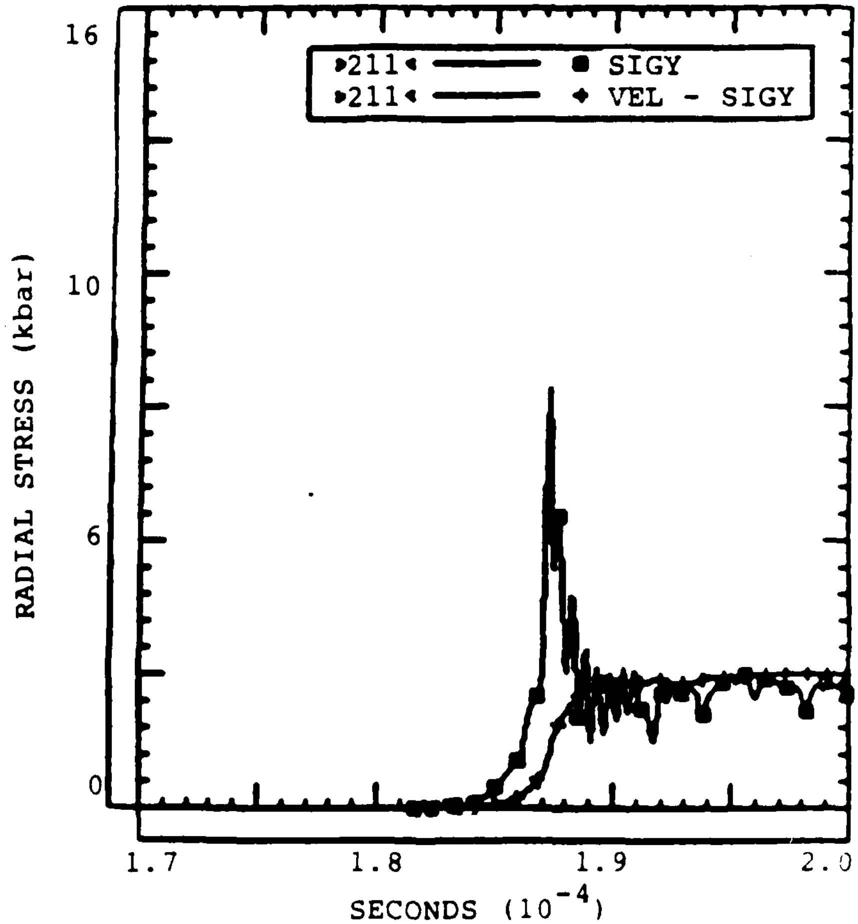


Figure 25c. Results of CRALE 1-D surface burst loading on alluvium and alluvium with idealized stress gage (Comparison of stress records with stress from σ = ρcv (with steel layer))

A simple analysis has been performed to examine the effect of variations in late-time velocity records on the differentiated strains. The example investigates changes in computed strains between two velocity gages in one-dimensional planar loading by considering a series of possible error magnitudes associated with different assumed velocity profiles. One-dimensional strain conditions are assumed to exist at the gage locations. Changes in the velocity release of only the more distant gage is assumed.

The peak velocity for Gage 1 is taken as 50 m/s and for Gage 2, 30 m/s (Fig. 26). Initial vertical gage spacing, L_o, was made reasonable by considering Reference 30. The decay portion of the 30-m/s velocity record was varied about an initial value, assuming a bilinear material. Corresponding strains were directly calculated from the velocity profiles. Figure 26 illustrates the procedure for ±10% variation of the initial slope. Strains were calculated from

$$\varepsilon = \frac{\int_o^t v_1 dt - \int_o^t v_2 dt}{L_o} \tag{29}$$

where L_o was the initial distance between gages. Table 2 summarizes the results and Figure 27 presents them in graphic form.

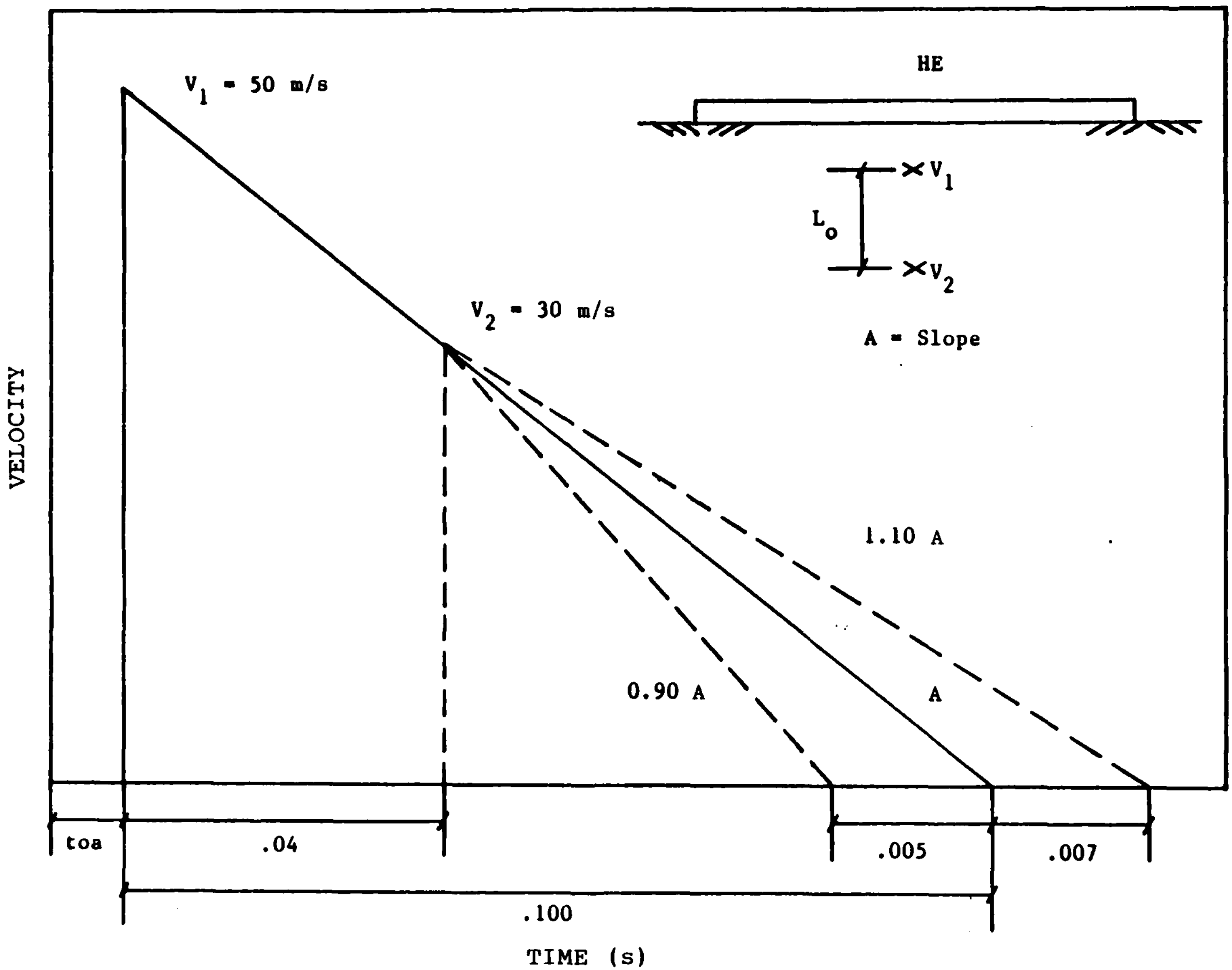


Figure 26. Idealized velocity-time profile used in analysis of variation of strain (a slope change of ±10% illustrating the procedure is shown)

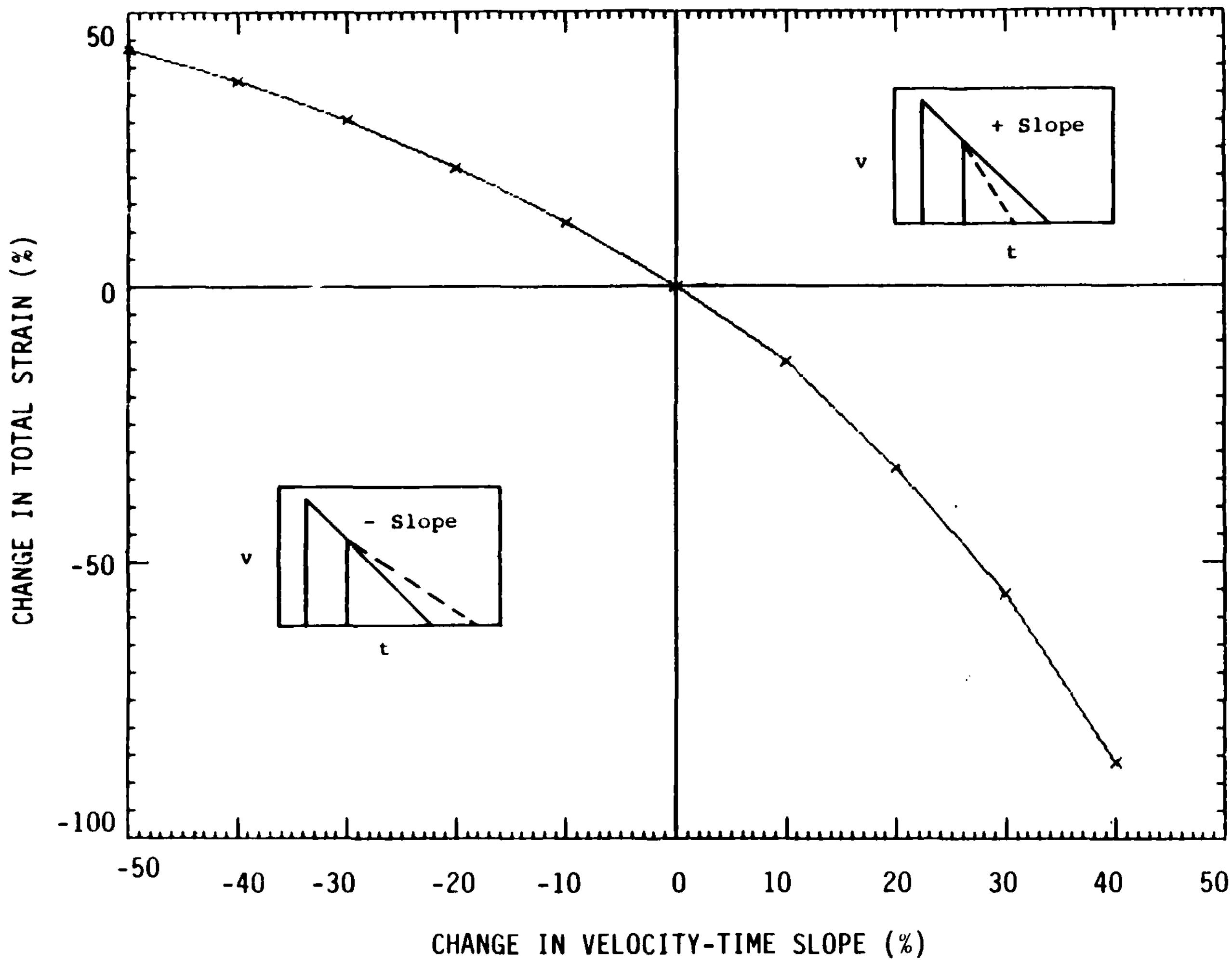


Figure 27. <u>Effect of variation in slope of idealized velocity-time profile on resultant strain</u>

Table 2. Errors in Strain Associated with Changes in Late-Time Velocities

Change in Slope (%)	Change in Total Strain (%)
-50	+43.4
-40	+37.5
-30	+30.3
-20	+21.7
-10	+11.8
0	0
+10	-13.8
+20	-32.9
+30	-56.0
+40	-86.2
+50	>-100.0

(Note: negative strain indicates a decrease in value.)

From Table 2 and Figure 27, it can be seen that changes in the magnitude of the slope of the velocity-time curve have a pronounced effect on the resulting strain. If the velocity profile underestimates the "true" record, then the error in strain increases more so than if the velocity profile is overestimated. A variation in slope of +10% or -10% produces about the same effect on the strain. But above these values, the difference in the influence on strain becomes more pronounced. This observation clearly indicates what can be associated with late-time velocity data.

The final error analysis is a simple comparison of arrival times of the velocity signal. Figure 28 shows a direct comparison of the data, in particular the rise times, for the velocity data. At any one range, differences in times could be attributed to errors in gage placement (both placement of the hole and the gage within the hole), recording errors (usually on the order of tens of microseconds) or differences in travel

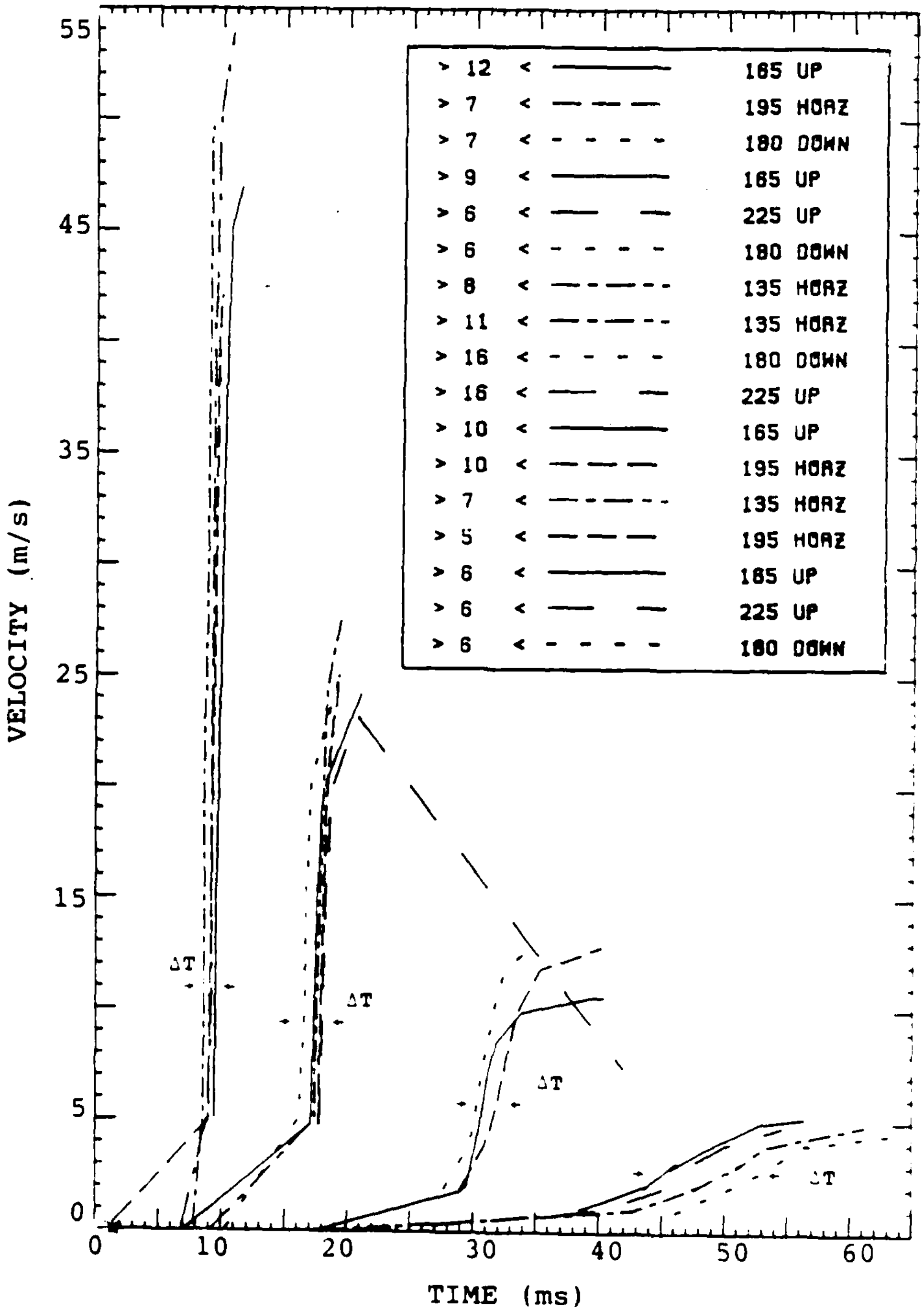


Figure 28. Radial velocity rise times for individual gages

paths, i.e., geologies. In this test, an attempt was made to place holes in approximately the same radial position. All of the presented gages were presumably at the same range. Nevertheless, an error of 0.01 m would lead to a timing error of 0.002 ms. For the gages farther out, the error (ΔT) is on the order of 5 to 10 ms. If the times of the different arrivals (ΔT) are plotted with respect to travel times, random errors associated with gage placement would not be related to travel times. That is, the plot should be a constant DC offset if only gage placement were an unknown. On the other hand, if the error were due to uncertainties in properties, the farther-out gages might be expected to have increased errors. The regression of ΔT with respect to travel time would be linear.

Figure 29, shows ΔT plotted with respect to travel times. It appears to be a combination of both random errors ($t <$ ms) and geologic errors given by

$$\Delta T = \begin{cases} 2 \text{ ms}; \; t < 28 \text{ ms} \\ 2 + 0.318\,(t - 28); \; t \geq 28 \text{ ms} \end{cases} \qquad (30)$$

The data indicate that arrival times are expected to be within only 15% of the "real" value if the error is geologic in nature.

Since σ and/or v depend upon propagation velocity through the impedance parameter,

$$I = \rho_o c \qquad (31)$$

This leads directly to the result that stress and velocities can vary by 15% due to natural differences of mechanical properties. Better than ~15% in peak velocities or stresses may not be achievable.

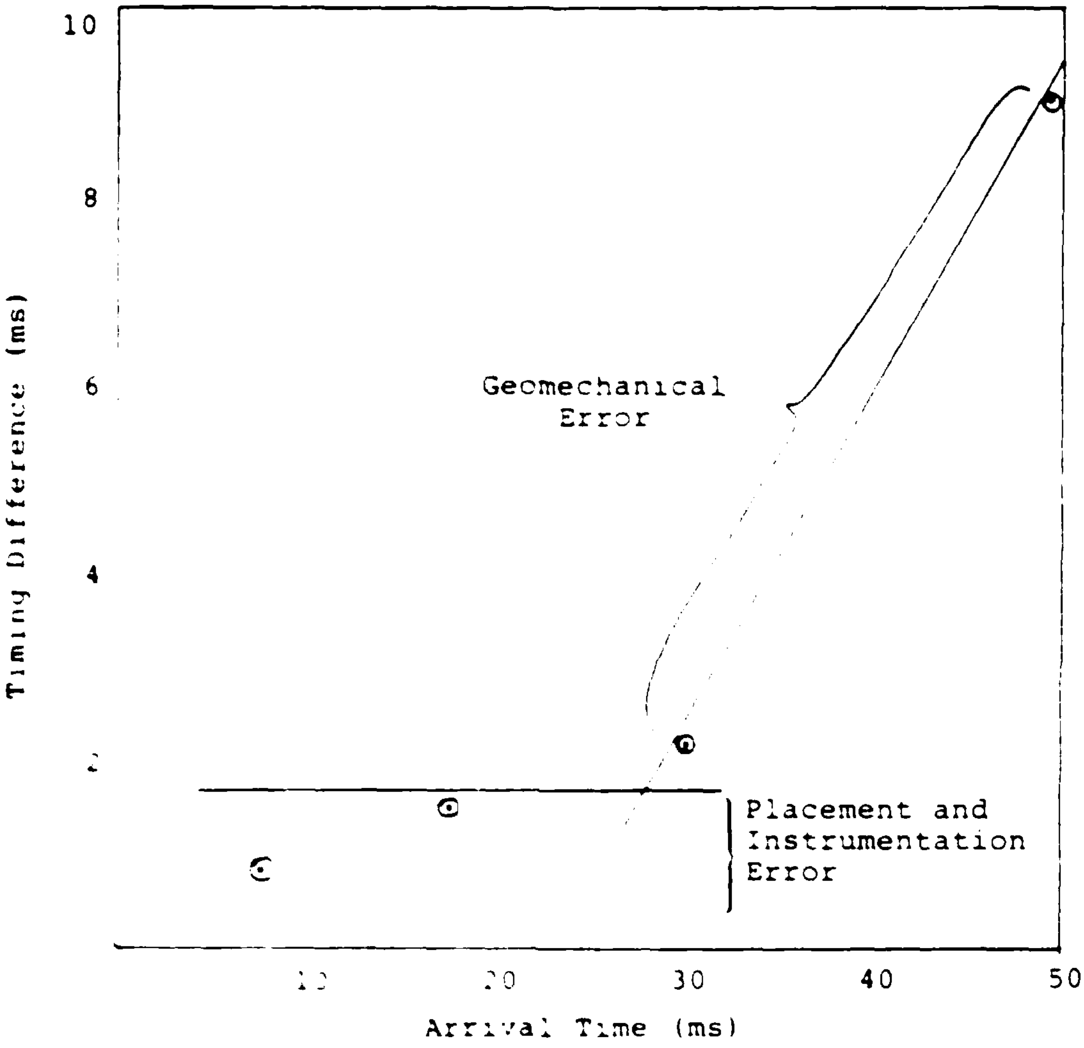


Figure 29. Timing errors with respect to travel times

AD-A180 694 MATERIAL PROPERTIES TEST 2 (MP-2) REVIEW AND FINAL DATA 2/2
ANALYSIS..(U) CALIFORNIA RESEARCH AND TECHNOLOGY INC
ALBUQUERQUE NM E J RINEHARD ET AL. SEP 87 CRTA-3751F
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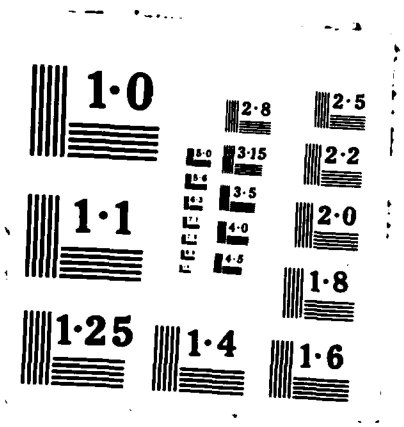
1·0
2·8
2·5
3·15
2·2
3·5
1·1
2·0
4·0
1·8
1·25
1·4
1·6

SUMMARY

Some new conclusions based on the preceding analyses are:

a. If nonrate dependent soils are assumed, the stress gages are substantially high. One-dimensional analyses support an inertial effect of the stress gages.

b. The one-dimensional analyses show that the sharp peak in the stress gage record cannot be attributed to impedance/transmission effects due to the extremely short transit time through the gage.

c. Stress gages are correct after about 30-60 μs. True peak stress occurs after that apparently reported from the stress gages.

d. The data neither support nor refute additional strains after peak stresses are reached. Baseline shifts and poor late-time velocity measurements can lead to very large errors ($\approx$ 50%) in calculated strains.

e. Error analyses of TOAs lead to the proposition that a 15% error in peak velocities and stress is a natural result that cannot be improved upon.

REVIEW AND RECOMMENDATIONS

REVIEW

a. MP2 provided velocity-time histories up to and including 80 m/s and stress-time histories up to and including 800 MPa.

b. The early portions of the stress and velocity records ($t < 60$ μs) were inconsistent with one another. The velocity records appear to be a better representation of the flow field.

c. <u>Assuming that velocity gages are correct</u>

(1) Material properties were determined which were little different than pretest modified lab estimates.
(2) Strain rate effects are not readily apparent.
(3) Later-time shear enhanced compaction can be postulated; however, the data are insufficient to prove or disprove the concept.
(4) Stress gages appear to be correct for times later than 60 μs.

d. A more than adequate data set was obtained with only 40 or 50 gages.

e. Analysis indicates that one may not now be able to obtain better data than reported because of natural effects.

RECOMMENDATIONS

The test provided high quality data for a spherical test in alluvium. Much was learned concerning instrumentation, cable hardening, limitations of data and how to measure high velocities and stress in alluvium. The test also provided controversy, especially concerning material models that could not be addressed with the available data. Better data are not expected in the future. Natural occurrences of 15% differences seen and explained preclude this. The test should not be repeated solely on this basis.

Results concerning the material properties actually measured with MP2 data support the "best estimated in situ" results obtained in the lab. The data provided no new firm results, perhaps because so much is already known about dry alluvium. The test did not supply any information concerning shearing and stress differences, although it was purported to do so. Considering no new results were obtained and the difficulty in fielding the spherical test, further tests of this type are not warranted in dry alluvium.

If a new material (wet soil, rock, etc.) were under consideration, and the detailed knowledge were not in hand, as in the case of dry alluvium, it would be important to have some sort of in situ test to validate the laboratory results. We would, however, recommend a cylindrical test rather than a spherical one, because the analysis would be approximately the same with similar results, except:

a. Test site homogeneity is not required.

b. The CIST is easier to field.

c. There exists a broader data base (CIST's, Reference 9).

d. The geometry allows different materials to be tested (e.g., layering).

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APPENDIX A

CORRESPONDENCE CONCERNING MP2 RESULTS

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7 December 1984

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The Technological Institute
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Evanston, Illinois 60201

Enclosures: As noted in the attached "Notes and References"

Dear Ted,

At the close of yesterday's meeting, you asked how CRT's stress-strain curves could be much in error when their pre-shot calculation for Event MP2 produced such accurate stress and velocity data. My answer was that, examined in detail, the calculation wasn't very accurate. I'd like to expand on that now; the story isn't long, but at the meeting I lacked the VU-foils needed to keep it short.

1. Peak Radial Velocity (U_{max}) vs. Slant Range (r): In Event MP2, the region of successful ground-motion measurement ran in slant range from 5.22 m to 30.05 m. Over that region, all of CRT's pre-shot curve of peak velocity (U_{max}) vs. r lies above, but near, the linear regression fit (on log-log paper) to the measured peaks.[1] The factor separating the two curves runs from 1.1 to 1.5 (typically 1.25 to 1.45), according to data from the calculation given to me by Ken Kreyenhagen (Fig. 1).[2]

The standard deviation of MP2 data-points from the regression line through those points, amounts to a factor of 1.43. Curves from four of the five pre-shot calculations fall within a standard deviation of the regression line (or nearly within, like CRT's); so does one of the two purely empirical estimates of U_{max} vs. r (6., below). A quadratic regression-fit to the same MP2 data proved no more accurate than the linear one; corrections to power-law decay of peak radial velocity aren't statistically significant.

2. Rise Time to Peak Velocity: Except for the smallest ranges that yielded in-situ velocity pulses, the calculated pulses show much shorter rise times than those measured - and judging from yesterday's discussion by CRT of their use of artificial viscosity, much of each computed time-to-peak is probably numerical in origin. In fact, as Fig. 2 shows, the computed and measured rise-times depend differently on r. The potential importance of those times to BMO is noted in Enclosure 1 (from which Fig. 2 was taken).[3] In line with those notes are comments of the BMO/TRW people at the meeting, to the effect that structural problems (if any) posed by ground motion stem from the first few tenths of a second of motion.

3. Peak Radial Stress ($\bar{\sigma}_r^M$) vs. Slant Range (r): In Event MP2, σ_r^M-values were measured by stress gauges. They also came from upper and lower bounds on radial stress, σ_r, obtained by coupling measured motion with the laws of motion; the bounds are then implied, respectively, by shear-strength and hydrodynamic limits of material behavior.[4] Stress-gauge-values of σ_r^M consistently exceeded the upper bound from motion gauges (Fig. 3). In particular, regression lines fit to the upper-bound peaks and to the stress-gauge peaks differ by a factor that runs from 1.45 at r=5.2 m (the smallest range of successful motion-measurement) to 1.1 at 14 m (the greatest stress-gauge-range); corresponding factors for the lower motion-bound are 1.45 and 1.55.

Values of σ_r^M from measured motion scatter less than the stress-gauge peaks, and are otherwise more credible for four reasons: a) First arrivals in accelerograms scatter less than those of the stress-gauge records (Fig. 4), and are also much more coherent (closer to forming a simple curve). b) The accelerometers' times of first arrival are consistent with the medium's independently-measured seismic P-wave speed, while stress-gauge arrivals (which all occur later) are not. c) In the stress-gauge records, precursors are sometimes clearly seen, sometimes absent, and sometimes hard to make out - but in a way that has little to do with r (5., below). On the other hand, motion-gauges plainly show an outgoing wave that broadens as it moves;[5] the Scooter event, with different motion-gauges than were used for MP2, gave the same result.[6] d) Stress is inherently harder to measure than motion;[7] for that reason (and others less basic), a secondary objective of MP2 - from the outset[8] - was to use measured motion to evaluate stress-gauge output.

Calculated values of σ_r^M, also plotted in Fig. 3, match the stress-gauge peaks fairly well - but the motion-bound peaks are more probably correct. Conclusion: The calculated peaks are high by a factor that runs from 1¼ at r=5.2 m to at least 2.2 (but ≤3) at 14 m.[9]

4. Velocity Waveforms: At the smaller of the ranges where accelerometers gave credible records (r<10m), MP2 velocities present a muddy picture of decay from peak values (Fig. 5). That fact has caused much concern in deducing strain paths and stress bounds from MP2 data, limiting the usable period of velocity decay to a minor fraction of the time over which most of the measured pulses are spread.[10] Thus, after peak velocities are reached, MP2 measurements say little about the accuracy of calculated waveforms; all pulses supplied before the shot (calculated and empirical) "fit" the data. However, as par. 2 (above) suggests, pre-shot and observed waveforms exhibit notable differences in the rise to peak velocity. The figures of Ref. 5 state those differences explicitly in terms of waveforms, which appear there for a) all the credible MP2 velocity pulses, b) pre-shot pulses calculated by ATI, CRT, Pac Tech and AFWL (only NMERI's are missing), c) ATI's empirical prediction (ARA's didn't include waveforms), and d) the Scooter event, simply scaled to MP2 yield. For ease of comparison, VU-foils of the figures are enclosed. Laying the pre-shot CRT pulses on those measured makes explicit the wave-form differences underlying Fig. 2 - but those differences are clearer in Fig. 2, because slow velocity decay in Yuma alluvium makes the rise to peak look abrupt in all but the 12.6-m pulses (the most distant shown). In the rise to peak, at least, Scooter affords the closest match to MP2.

5. Measured Radial-Stress Pulses: Upper- and lower-bound pulses of radial stress deduced from measured motion (3., above), are compared with stress-gauge output

in the figures of Ref. 11. The comments above (3.) on the two types of stress pulse (motion-bounds vs. stress-gauge) can be verified from those figures. In addition, the stress-gauge pulses at all ranges but 14 m (the farthest) show a hard-to-believe tendency to level off, and then rise again, after decaying to ½-to-¼ of $\hat{\sigma}_r$. Such behavior seems unlikely in this free field, but, at the smaller slant-ranges, could plausibly result from interaction between a gauge-structure and the medium.[7]

6. Velocities, Pre-Shot and Predicted: CRT's calculated (pre-shot) velocities had reasonably accurate peaks, and waveforms not much less so. Evidently, the same can be said of Pac Tech's velocities, even though Pac Tech's model was rate-dependent and CRT's was not (some cause for unease). AFWL had similar success. ATI, with an FFGM-type model much like CRT's (FFGM≡Free Field Ground Motion), came closest to giving the observed power-law fit to peak velocity; also, while our spiky waveforms look worse than CRT's, differences in smoothness between the two stem mainly from an artificial viscosity CRT used in unloading (an invention of mine, about which I've evidently had second thoughts; artificial viscosity is of course not a material property).

The rise-time tale is grimmer, though Pac Tech's (and perhaps ATI's) bear some resemblance to observation (for physical reasons, not numerical). But let all that pass. Trouble really starts when any of these calculations is mistaken for a prediction. Little if anything was predicted in them about MP2 motion, because, before MP2 was fielded, a lot was known about its motion from measurements made in earlier events. Using that knowledge alone, two empirical pre-shot estimates were made of MP2 velocities. In fact, Fig. 1 blossoms into Figs. 6, 7 and 8 when the full set of estimated MP2 velocity peaks (empirical and computed) is assembled.[13] True, the empirical estimates in those figures are somewhat less accurate than the model-curves. But then, the calculations outnumber them 5-to-2. Had five empirical estimates been made, they too would most likely have fallen around the MP2 regression line. That's because a) initial conditions in the Scooter event were most like - and much like - those of MP2,[14] and b) the Scooter regression line is virtually identical to the MP2 line (Fig. 8). Scaled-Scooter waveforms do differ significantly from MP2's, showing longer rise-times, but Scooter's rise times present a better match to MP2 than was obtained from any pre-shot estimate. The empirical waveforms, on the other hand, are not as accurate overall as CRT's (being more accurate than CRT's only at 14 m, after much dispersion has occurred).[15]

When the data-base for a given event (e.g., MP2) includes shots as similar to it in design and medium as Scooter was to MP2, and measured motions turn out as similar as those of Scooter and MP2, then the event is of sharply limited use as a means of validating models: By way of motion, not enough is left to predict for the event to serve that function. As regards MP2, none of this is hindsight; for the reason just stated, ". . .MP2 was not billed as a test of model accuracy."[5] Moreover, claims that Scooter data had no effect on one or another pre- or post-diction of MP2 fall flat. Why? Because[5] ". . .modelers themselves can't be sure [of such claims]* after long exposure to the data-base (and given their professional charge to keep abreast of it)." More bluntly: The odds are long against seeing a prediction-calculation for MP2 (or for any buried charge in dry desert alluvium) in gross conflict with Scooter data (or even with a consensus of motions measured for buried bursts in dry desert alluvium[16]). The fact is that the modeling process is biased by the base of in-situ data that precedes any given shot, and the wider

*Bracketed phrase added here.

the base the greater the bias.[17] Furthermore, there's nothing wrong with that bias. However, failure to recognize it when evaluating pre-shot calculations, can be badly wrong - and it is for MP2.

At bottom, the point here is quite simple: You can't predict something you already know. To say otherwise is a contradiction in terms,[18] and a misleading one. As for establishing what we "already know", the cleanest and simplest approach at present is to make predictions from nothing but earlier free-field measurements - "empirical predictions". The case for such predictions as a measure of the extent of possible model-validation, is overwhelming. Not enough of them preceded MP2, but the two that did (only one with waveforms) are indispensable for putting comparisons like those of Figs. 6 and 7 into correct perspective.

7. Radial Stresses, Pre-Shot and Predicted: Ref. 5 states that "Since the pre-MP2 data-base contained none of [the stress-strain curves deduced from measured MP2 motions] . . . they definitely provide a test of the MP2 models . . .". So framed, the statement means: MP2 models can be validated on the basis of radial stress even if ground motion provides no basis for their validation. These assertions are false (though in the limited sense of 8., below, the stress-strain curves deduced from MP2 motion do provide a critical test of the MP2 models). The problem with them (as the figures of Ref. 11 show) is that the MP2 motion-pulses, taken with the laws of motion, set close upper and lower bounds on radial stress. Hence, radial stress does not offer an independent criterion for validating models: Over the whole time covered by the radial-stress bounds of Ref. 3, accurate motion-pulses imply accurate radial-stress pulses (and vice versa). Hence, adjusting a material model to give reasonable velocity pulses forces it to give reasonable radial stresses as well. Pre-shot knowledge of the MP2 velocity field from an earlier event like Scooter thus skews the whole process of evaluating the pre-shot models.

Of course, radial-stress bounds can be close only if hoop stress has little effect on motion - and then any physically possible hoop stresses will be consistent with the motion.[19] Since hoop stress was not measured in an earlier event than MP2, and MP2 motion leaves it wide open, measured hoop stresses would "definitely provide a test of the MP2 models". However the measurement of hoop stress . not as far advanced as that of radial stress. It now looms as the more urgently needed of the two, but attempts to measure hoop stress in MP2 didn't succeed.

8. Volume Changes Due to Shear: With computed pre-shot velocities reasonably close to those of the MP2 field, computed strain paths and radial stresses should also fall reasonably close to those of MP2 (7. above - and strain fields follow rigorously from velocity fields). Hence, the same applies to radial stress vs. strain. Yet, a difference between actual and computed stress-strain behavior has emerged from MP2 that puts in doubt a cornerstone of the MP2 models (or any MP2 model of FPGM type), namely, the assumption that mean stress varies with volume strain alone. Now what turned good agreement into major conflict? Well, i) computed and observed velocity gradients (which define strain rates) don't agree as well as the velocities themselves, and ii) "good agreement" is a loose term; velocities in pre-shot calculations differ by non-trivial amounts from the mean of those measured (1., 2. and 4. above), even though the agreement seen in Figs. 6 and 7, and the figures of Ref. 5, looks "good". As it happens, in the most likely MP2 velocity field and plausible variants of it, the history of volume strain at r=5.2 m differs in one key way from that of AII's pre-shot calculation: After peak velocity and stress are reached, the MP2 volume continues to decrease appreciably (by ~4% of its initial value), while the computed volume grows (by ~1%) - even

though the strain paths look reasonably similar (Fig. 9). For the MP2 path, the attendant difference between the model's radial-stress pulse and that of MP2 is huge; owing to volume decrease on that path, the computed radial stress increases sharply while the radial-stress bounds for MP2 (and hence its radial stress) both fall. The same goes for CRT's model (Fig. 9).

9. Significance of the MP2 Event: Shear accounts for most of the strain seen in Fig. 9 after peak velocity is reached. However, the relatively small volume-component of that strain is compressive while all principal stresses become less so.[20] Thus, on strain paths actually taken in explosive fields, the MP2 data imply that stress is relieved by shear in Yuma alluvium. By contrast, it's a hallmark of FFGM-type models that mean stress shall be determined by volume history alone. Hence, if Fig. 9 is about right, the MP2 models (or any FFGM models of Yuma alluvium) are far wrong.

The argument that MP2 data support the models because their strain paths and radial-stress pulses "agree well" with those observed, is specious. To make it, one must wish away much of what the MP2 data have disclosed, including a) a basic and far-reaching error in the models' treatment of shear, b) non-trivial errors in the fields calculated with pre-MP2 models (1.-3. above), and c) the fact that the models added little or nothing to what was known about the MP2 field from motion measured in pre-MP2 events (6. and 7. above). Ignoring these points because they may be unpleasant, is indefensible. Moreover, in this case, "good agreement" between computed and observed strain paths won't wash; as Fig. 9 shows, a miss here is not only as good as a mile - it is a mile.

Of course, the MP2 field can be reproduced (with appreciable error) using pre-MP2 models, and more accurately with post-MP2 models - even if the models are basically incorrect, as the MP2 data suggest.[21] However, the latter outcome of MP2 (probable incorrectness of the models) far outweighs the former (reproducibility of MP2 with models). After all, the MP2 field holds almost no interest per se; nuclear threats don't feature bursts near optimum DoB. Rather, near-surface bursts drive the fields of prime interest; on most regions, strain paths are then more complex than MP2 paths and again present large shear-components. If shear-strain effects are as poorly represented in the models as the MP2 data imply, how can model-predictions of such fields be trusted?

The main weakness in the case made by MP2 for shear-induced stress relief, and against FFGM-type models, lies in the scatter and inconsistency of MP2 data.[22] While the most likely conclusion from the event is summarized in Fig. 9, the possibility of volume expansion as radial stress falls cannot be ruled out; the MP2 field is too uncertain for that.[23] At the same time, the stakes are so high that the likely conclusion can't simply be brushed off; the chance of spending many times the cost of MP2 on worthless calculations - or worse - is too real. Hence, the overriding, responsible conclusion from MP2 is that the shot should be repeated with better instrumentation.[24]

I'd certainly welcome your comments on any of these subjects.

Sincerely,

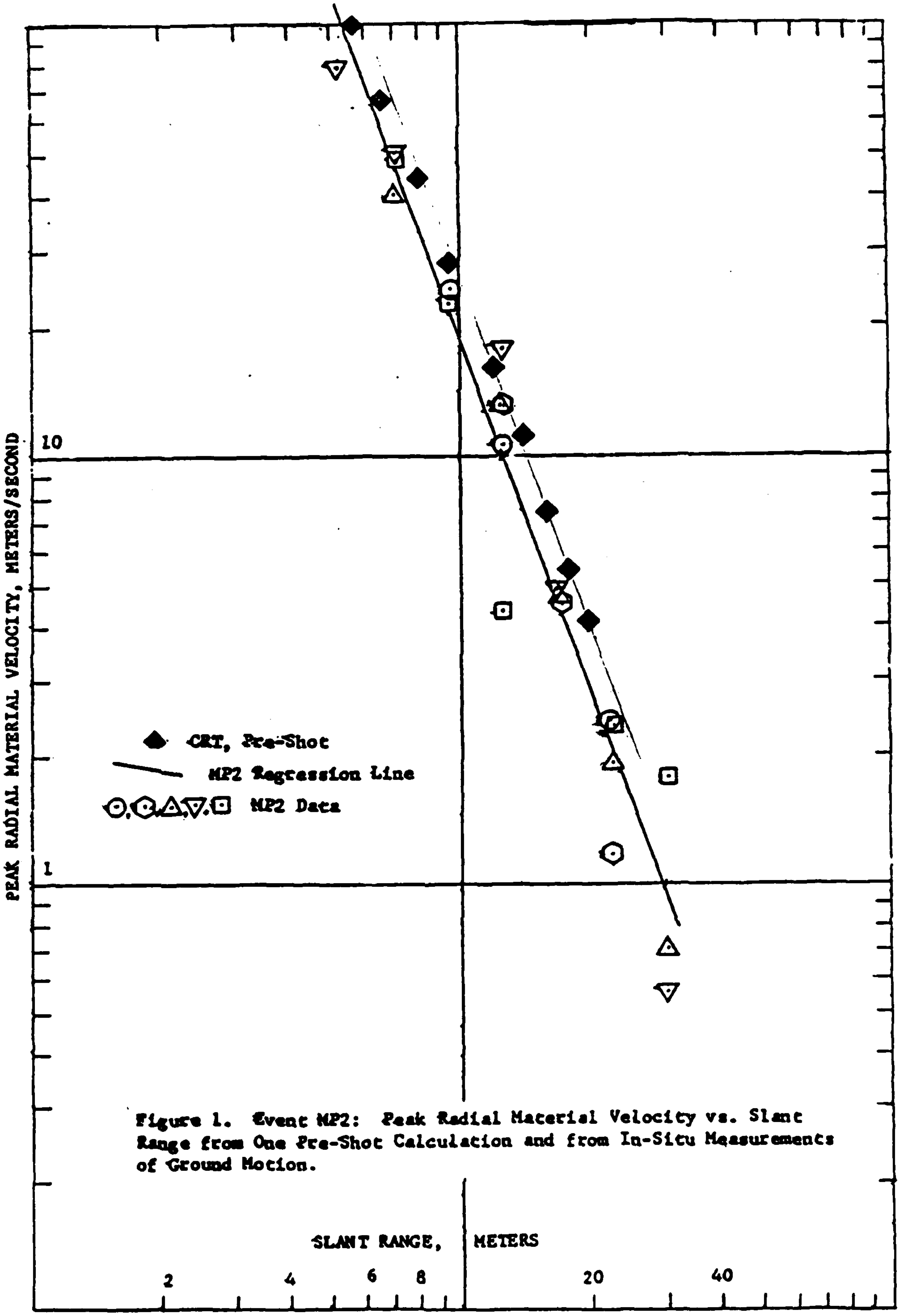

Figure 1. Event MP2: Peak Radial Material Velocity vs. Slant Range from One Pre-Shot Calculation and from In-Situ Measurements of Ground Motion.

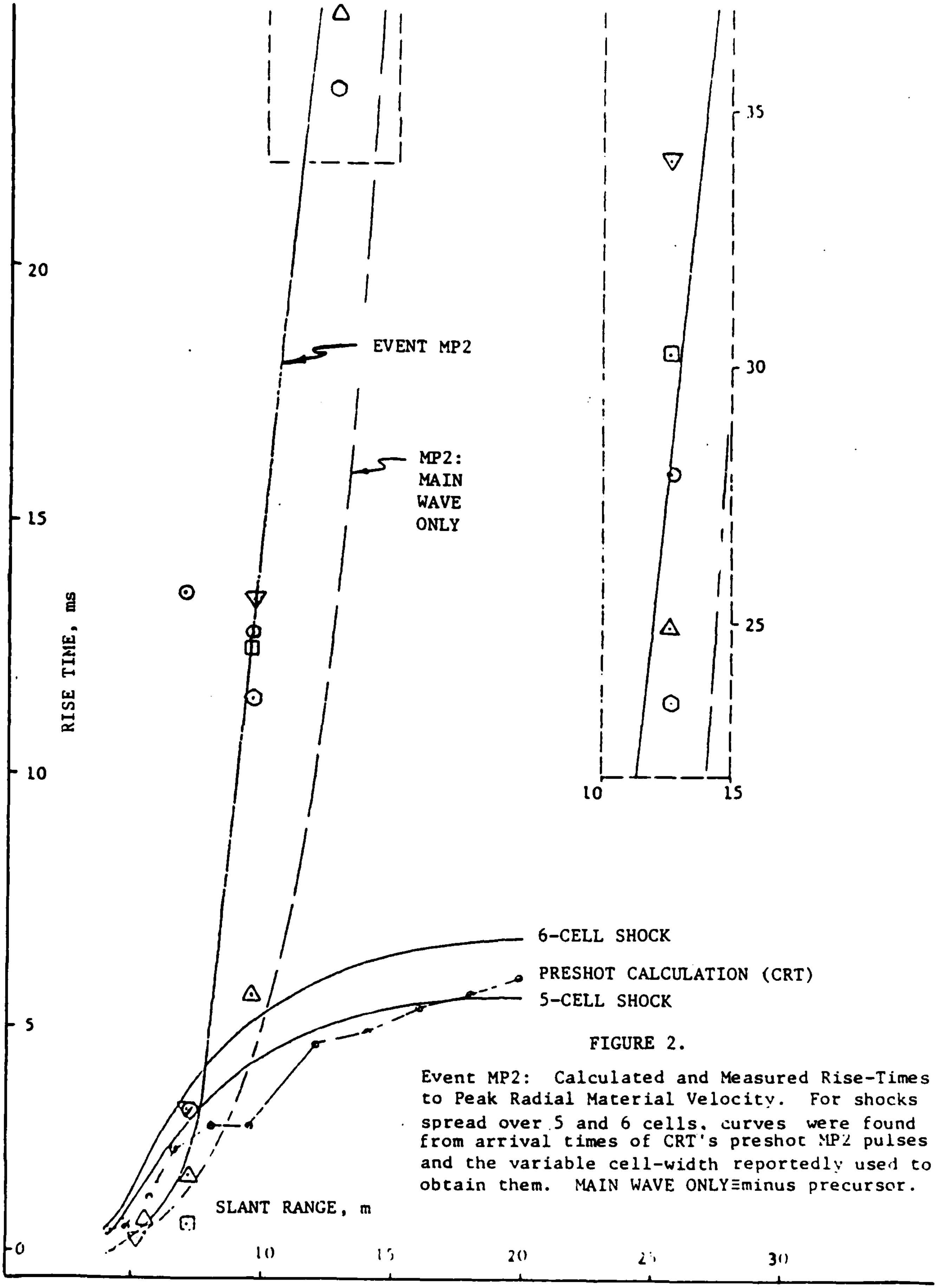

FIGURE 2.

Event MP2: Calculated and Measured Rise-Times to Peak Radial Material Velocity. For shocks spread over 5 and 6 cells, curves were found from arrival times of CRT's preshot MP2 pulses and the variable cell-width reportedly used to obtain them. MAIN WAVE ONLY≡minus precursor.

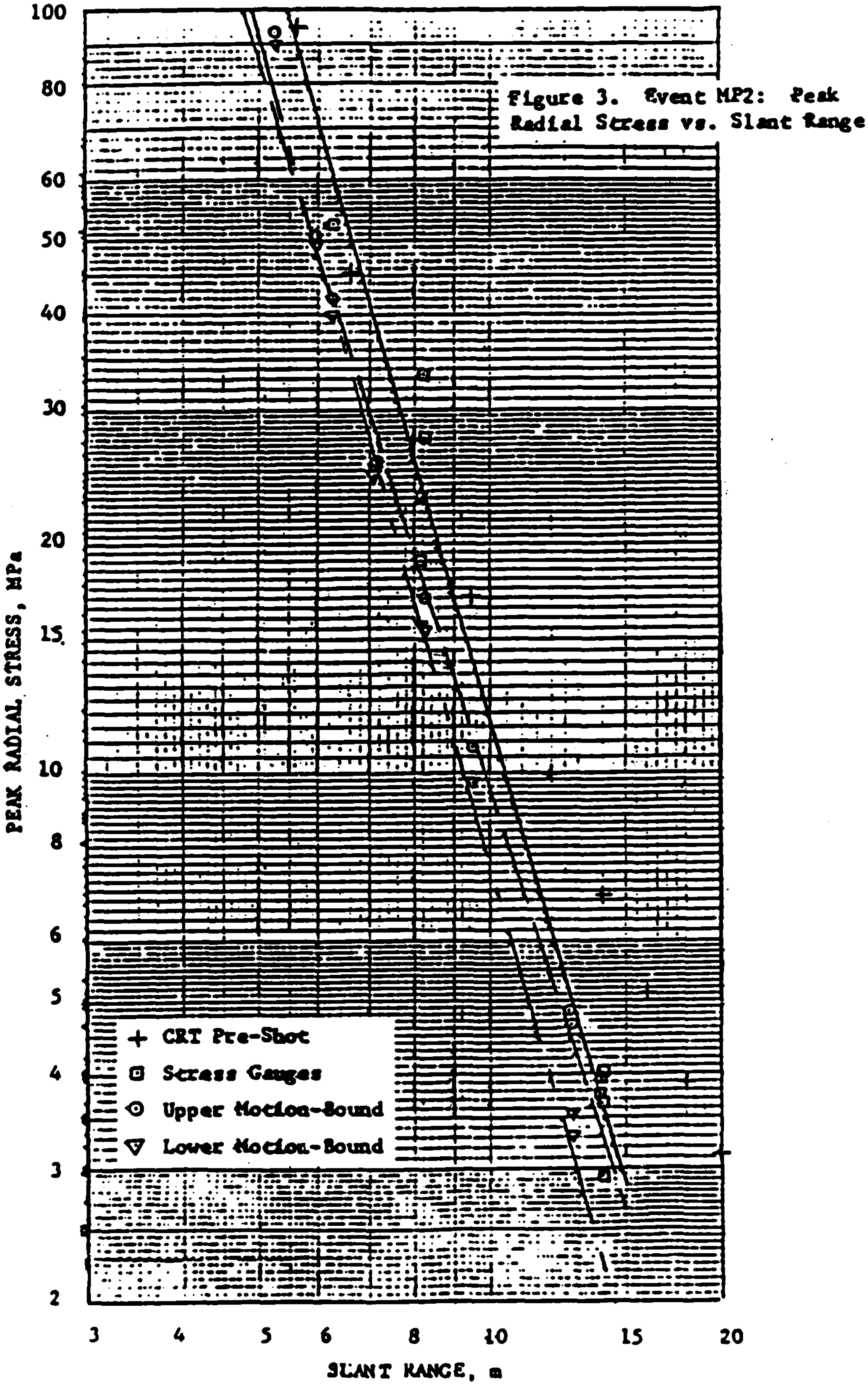
Figure 3. Event MP2: Peak Radial Stress vs. Slant Range
CRT Pre-Shot
Stress Gauges
Upper Motion-Bound
Lower Motion-Bound
PEAK RADIAL STRESS, MPa
SLANT RANGE, m
100
80
60
50
40
30
20
15
10
8
6
5
4
3
2
3
4
5
6
8
10
15
20

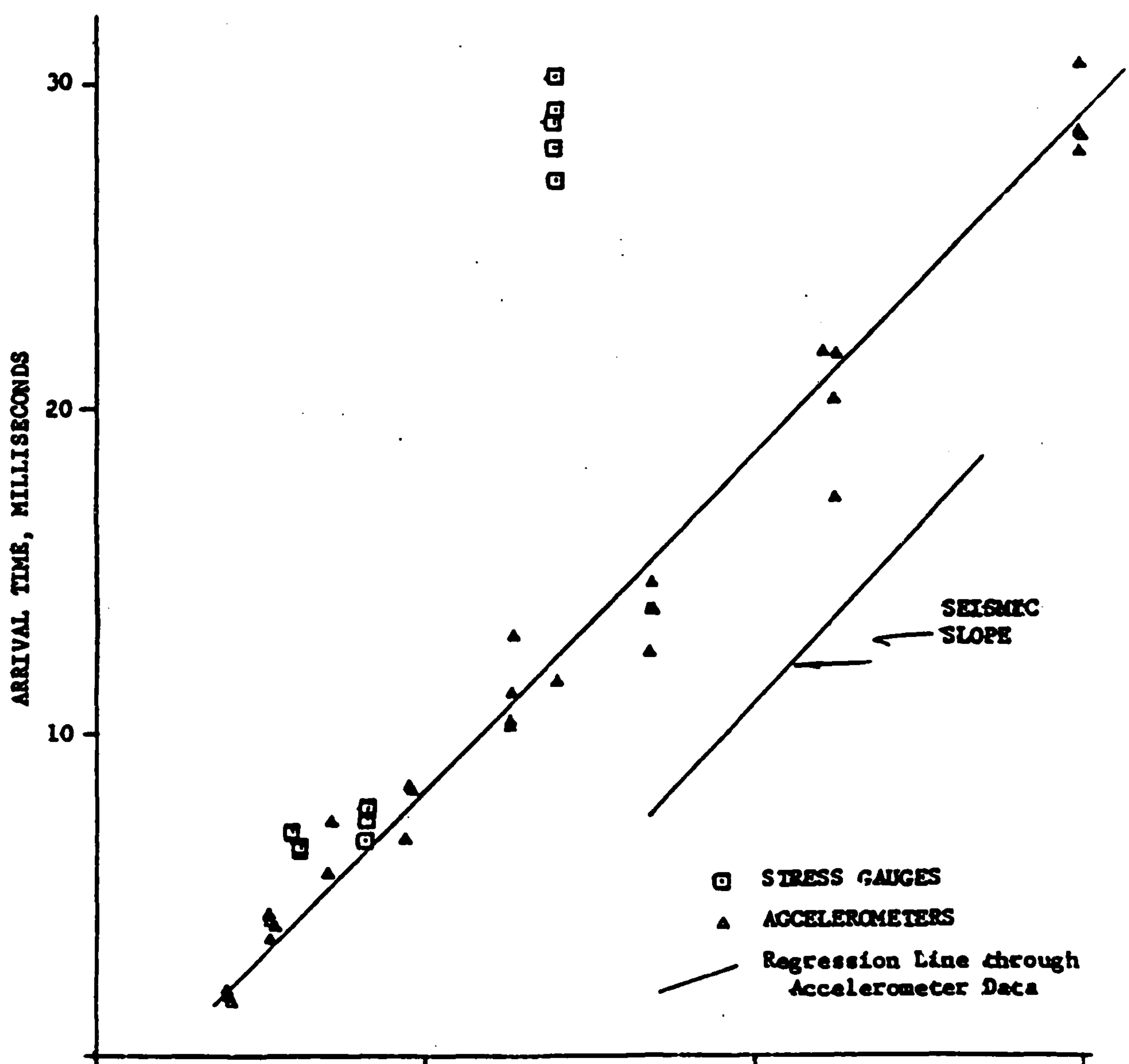

Figure 4. Event MP2: Arrival Time vs. Slant Range from Accelerometer and Stress-Gauge Records. The regression line through the accelerometer data is consistent with the measured seismic P-wave speed.

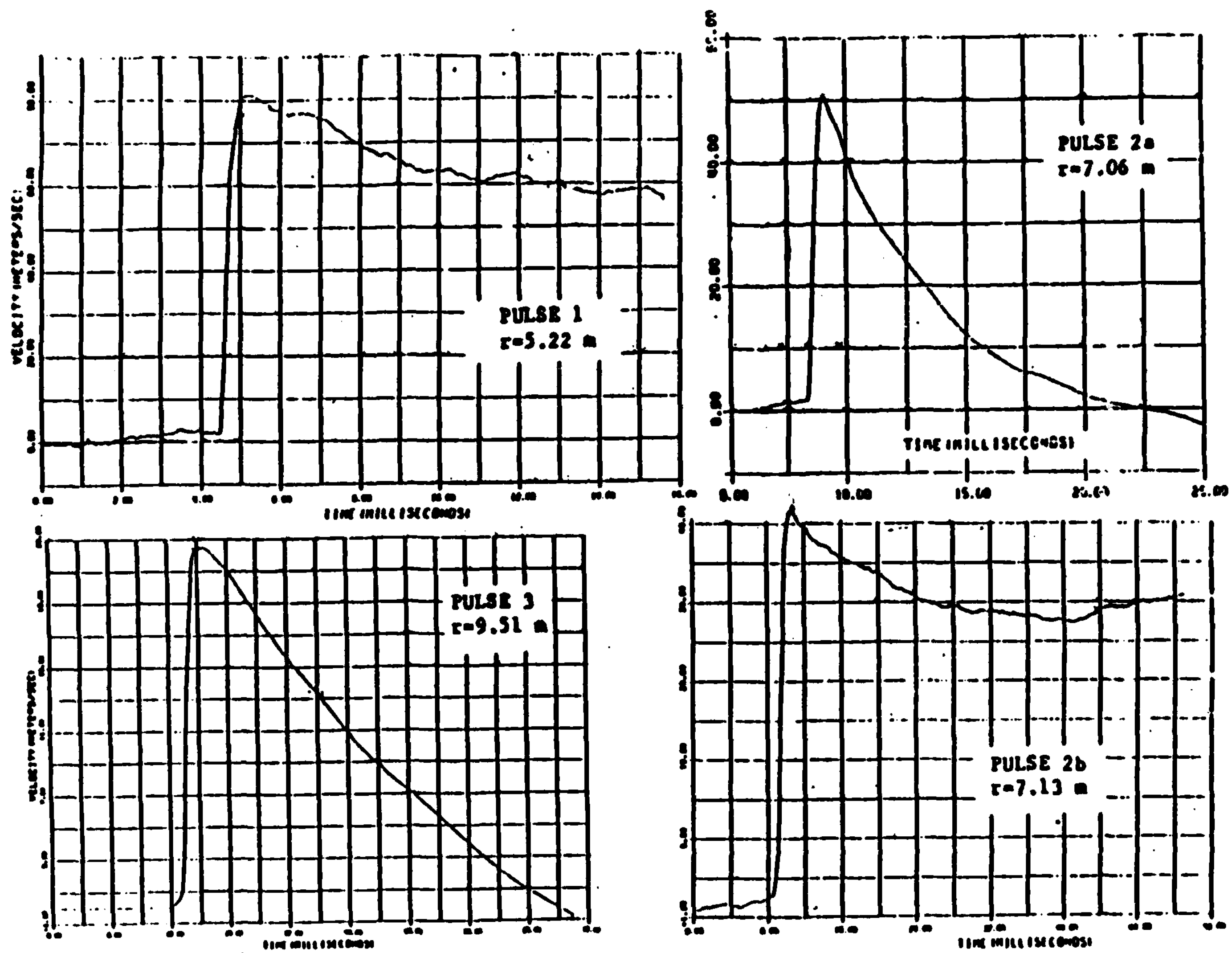

Figure 5. Velocity Pulses at the Three Smallest Radii of Successful Motion-Measurement in Event MP2. The pulses came from accelerometers at shot depth (Pulses 1 and 2a) and on an upward-slanting line (Pulses 2b and 3). Each consists of a low-amplitude precursor, a steep rise to peak, and then much slower decay. Except for Pulse 2a, the precursors here are mainly artifacts of measurement.

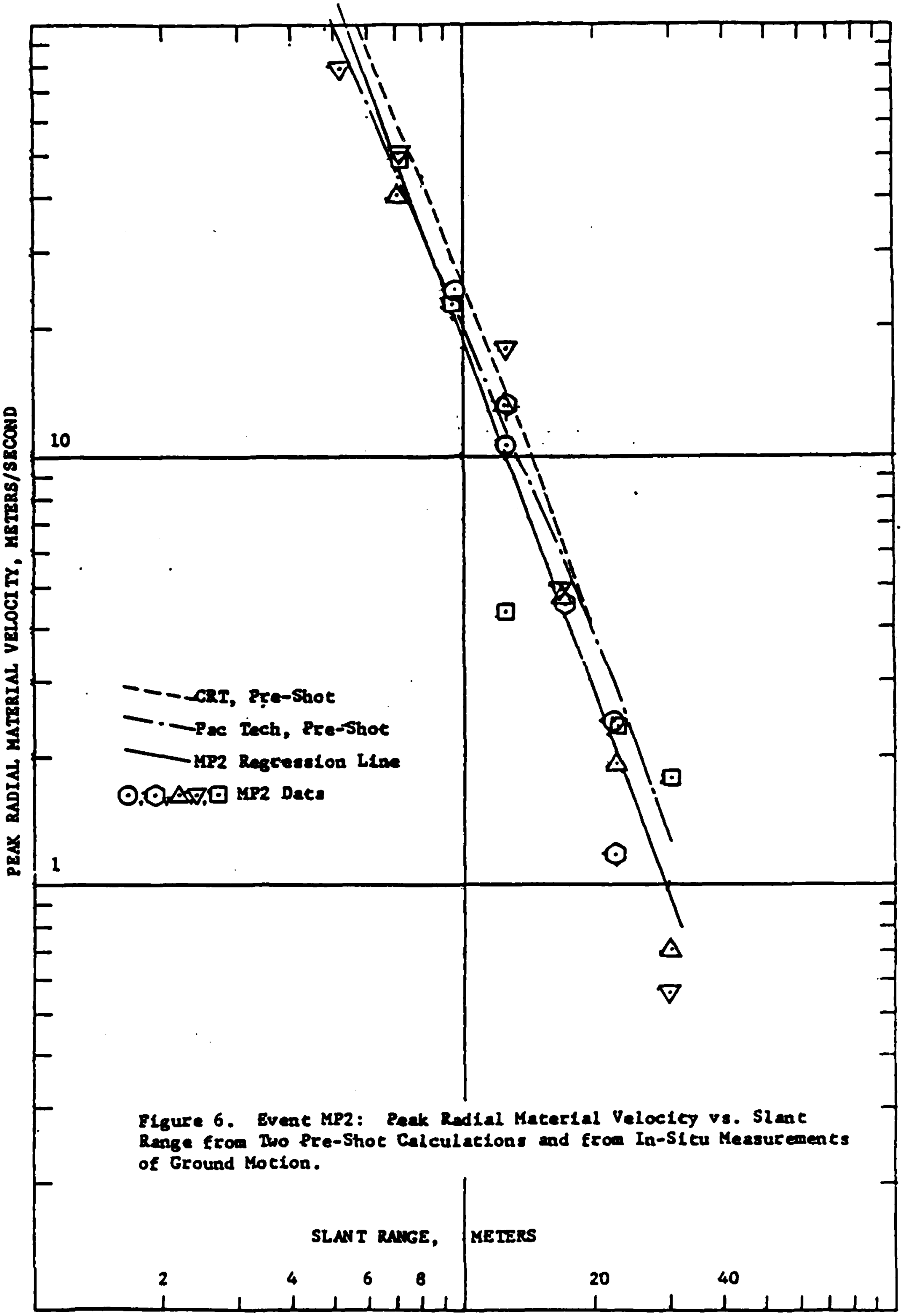

Figure 6. Event MP2: Peak Radial Material Velocity vs. Slant Range from Two Pre-Shot Calculations and from In-Situ Measurements of Ground Motion.

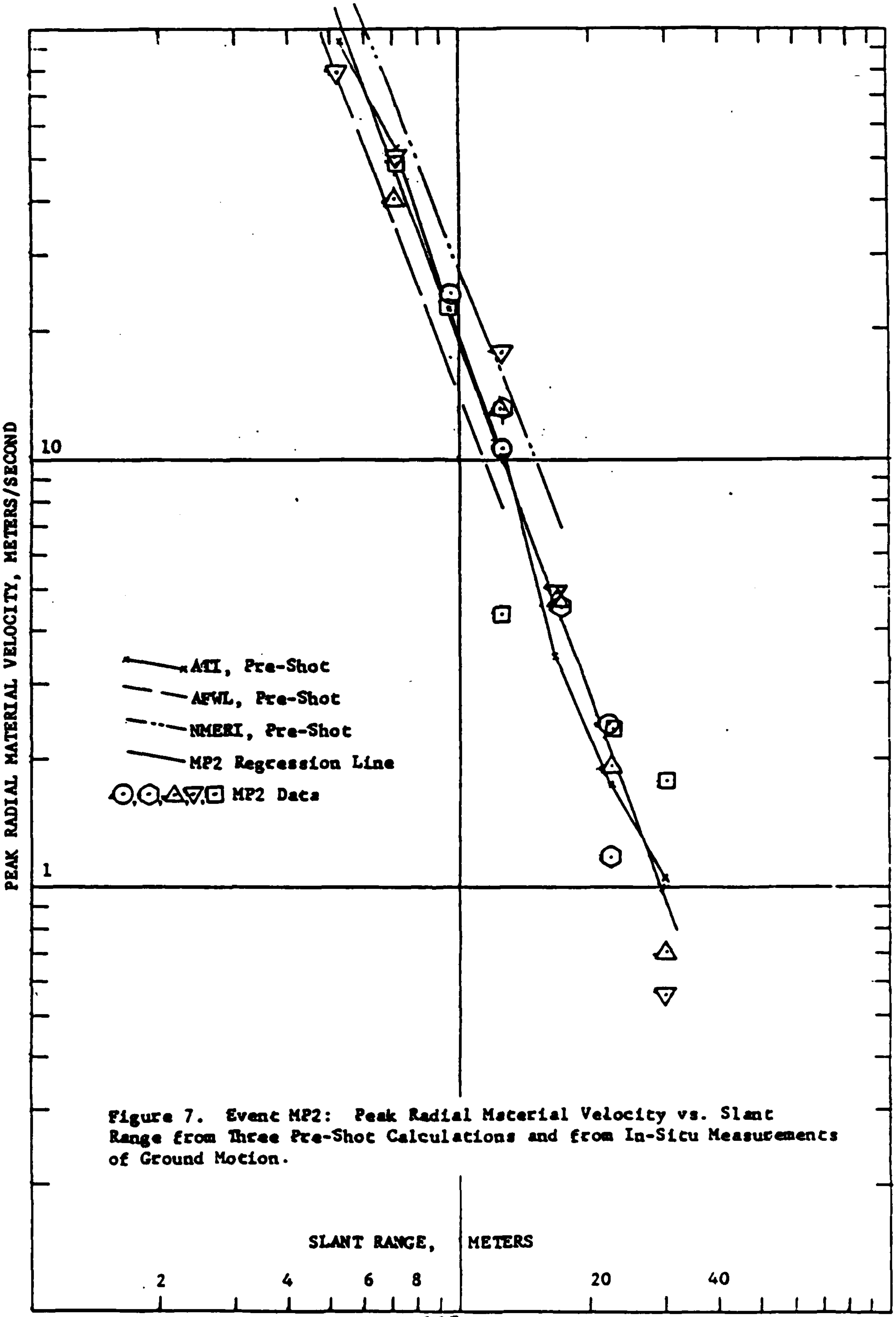

Figure 7. Event MP2: Peak Radial Material Velocity vs. Slant Range from Three Pre-Shot Calculations and from In-Situ Measurements of Ground Motion.

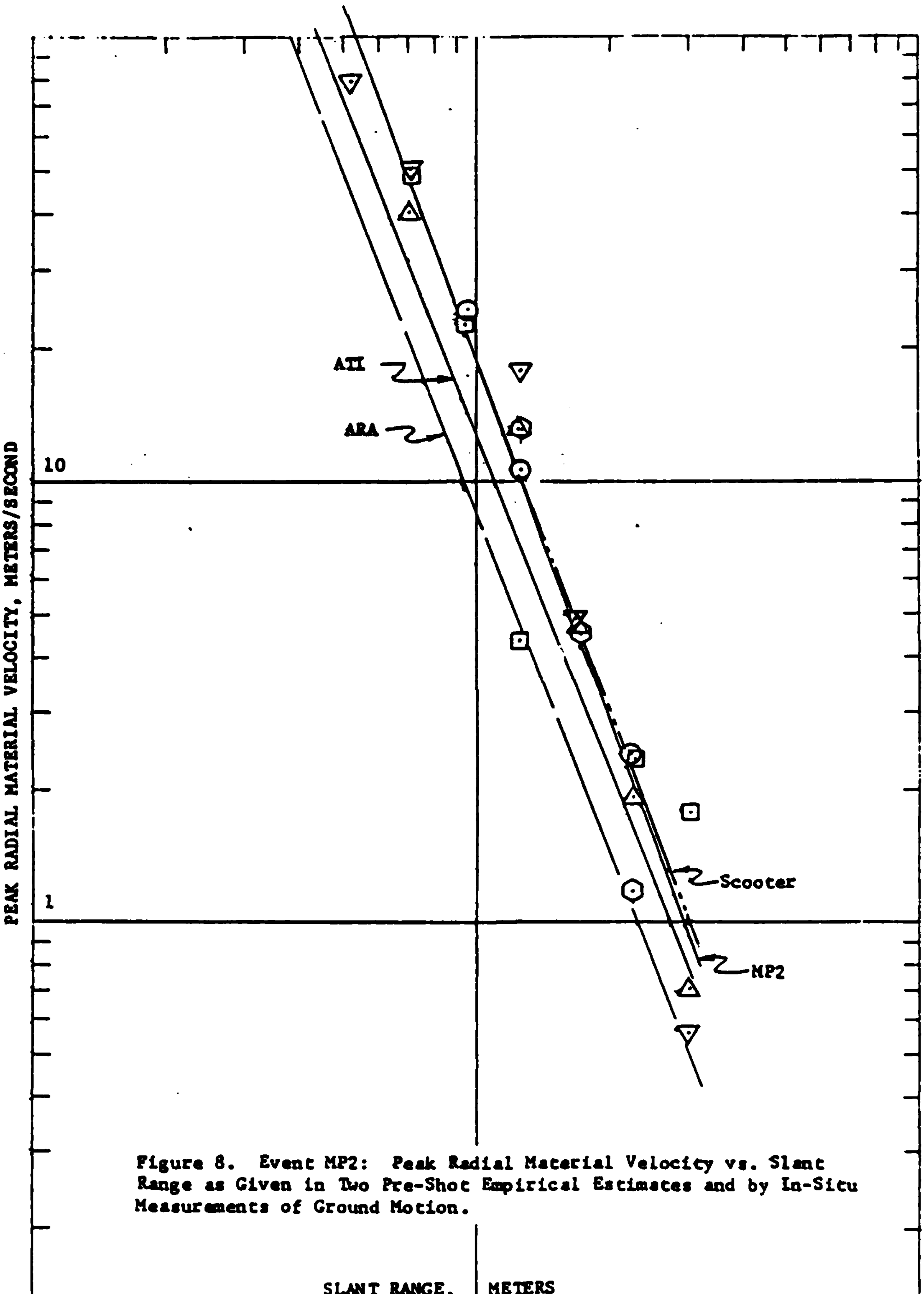

Figure 8. Event MP2: Peak Radial Material Velocity vs. Slant Range as Given in Two Pre-Shot Empirical Estimates and by In-Situ Measurements of Ground Motion.

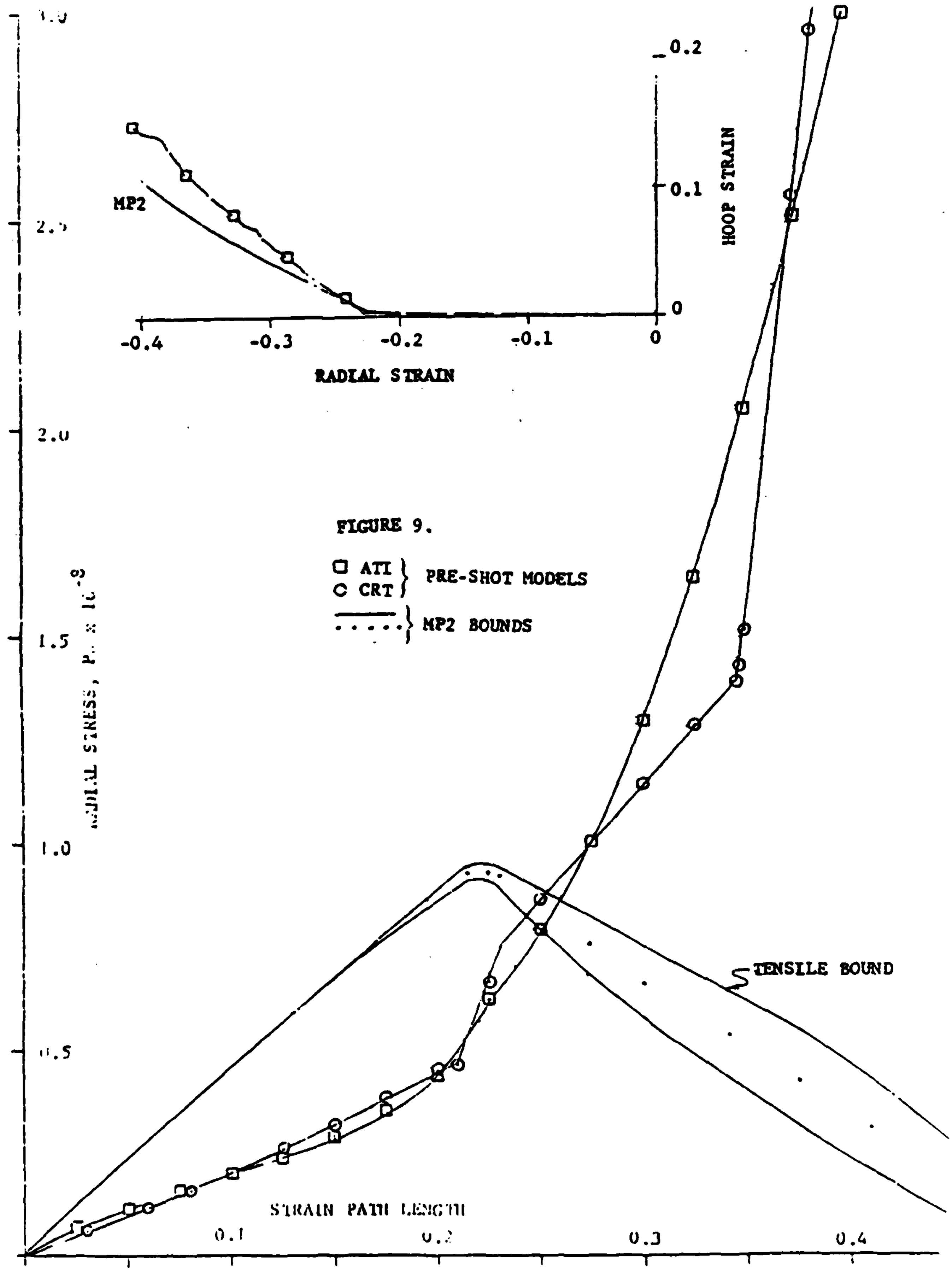

FIGURE 9.
ATI
CRT
PRE-SHOT MODELS
MP2 BOUNDS
TENSILE BOUND
STRAIN PATH LENGTH
RADIAL STRESS
MP2
HOOP STRAIN
RADIAL STRAIN
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
1.0
1.5
2.0

NOTES AND REFERENCES

1. Fig. 1 contains only peaks that were reached without obvious sizable error.

2. One of Ken's points differs by a small but significant amount from our reading of the AFWL summary of pre-shot calculations (Ref. 12 below), and his data extend to greater ranges than those of the summary.

3. Letter of 10/19-11/6/84 to J. Jones from J. Trulio. ENCLOSED

4. J. Trulio, "In-Situ Strain Paths and Stress Bounds, with Application to Desert Alluvium," Applied Theory, Inc. Technical Report No. ATR-84-65-1, p. 6, 7 and Appendix A (June 1984; submitted to DNA for publication on 22 August 1984), A draft copy of this report was sent to you on 4 January 1985.

5. J. Trulio, "Empirical and Theoretical Estimates of Ground Motion;" talk given at the "Meeting on Measuring and Estimating Material Properties," (Stanford Research Institute, 13-14 November 1984; proceedings to be published). ENCLOSED

6. W. Perret et al, "Project Scooter," Report No. SC-4602, October 1963 (Sandia Laboratory, Albuquerque, NM).

7. Inelastic interaction of a medium with a structure, such as a gauge, ends in a null velocity field, but not one of zero stress. "Locked-in" or "residual" stresses remain. Thus, the velocities seen by a gauge at late times are those of the free field, while the stresses are not; in general, long-lasting stresses alien to the free field develop around the gauge as it interacts with the medium.

8. J. Trulio and R. Port, "Material Properties for MX Land-Basing," Applied Theory, Inc. Report No. ATR-55-82-1, p. 16 (July 1982). ENCLOSED

9. Postdicted peaks shown at the meeting for "WLBM" alluvium present almost the same picture.

10. Ref. 4, Figs. 1 and 5 (bottom); p. 17, 32; Appendix B, p. 53-56.

11. J. Trulio, "Consistency of In-Situ Stress and Motion Measurements;" talk given at the "Meeting on Measuring and Estimating Material Properties" (Stanford Research Institute, 13-14 November 1984; proceedings to be published). ENCLOSED

12. Proceedings of the "Material Properties Test #2, Pretest Prediction Briefing," held on 21 November 1983 at the Air Force Weapons Laboratory (distributed by Dr. E. Rinehart). ENCLOSED

13. Letters from Applied Theory, Inc. to Dr. E. Rinehart, dated 29 November 1983 and given to Dr. Rinehart on that date, containing pre-shot empirical and computational estimates of velocity pulses for the MP2 event. ENCLOSED

14. In Event MP2 (11/30/83), a 10-ton sphere of nitromethane was fired 20 m deep in Yuma alluvium. In the Scooter event (10/13/60), a 494-ton sphere of TNT was fired 38 m deep in NTS alluvium.

15. Relative to waveforms, one major decision had to be made at ATI in producing empirical pre-shot estimates of MP2 velocity pulses, namely, whether to include MP3 data (248 lbs of TNT at McCormick Ranch; an instrumentation test) along with data from Scooter and MP1. We did. As a result, the empirical waveforms are less accurate than those computed (the statement to the contrary in the Abstract of Ref. 5 is incorrect).

16. W. Perret and R. Bass, Sandia Laboratories Report No. SAND74-0252, Section 3.2 (Printed February 1975).

17. Besides modifying models directly on the basis of comparisons with related, previously-measured fields, model-predictions are affected by the extant base of in-situ measurements in many subtler ways. For instance, guided by those measurements; a) artificial viscosities are adjusted so that numerical noise is cut to acceptable levels without too much rounding of peaks; b) unload-reload curves are given elastic tails to account for observed eventual recovery from outward displacement, or to otherwise power late-time motions; c) the equations, functions and parameters governing the growth of inelastic shear-strain are adjusted so that, in tandem with the equations, etc., for inelastic volume changes, velocities decay properly with range; d) elastic shear-moduli are made to vary as needed with the parameters of inelastic loading. Model-adjustments like these often occur not in single, clearly identifiable steps, but over extended periods as the cumulative result of many small adjustments (and associated calculations) - which is one reason why modelers tend to underestimate the role played by extant in-situ data in their "predictions".

18. In loose speech, a "prediction" is any statement about the outcome of an event before it occurs. On that basis, one "predicts" day and night in the next 24 hours. The word is not applied so lightly to scientific theories: A theory can be consistent with existing measurements of a quantity, but it can only predict for the quantity what is not already known from measurement. If we scrap scientific usage, then we'll have to distinguish between useful and useless prediction - and the models' predictions of MP2 would be largely useless.

19. Ref. 4, p. 11 and 59 (Note 2).

20. Ref. 4, p. 6 and 22.

21. J. Trulio, "Strain-Path Modeling for Geo-Materials," Defense Nuclear Agency Report No. DNA-TR-84-105, p. 14-16 (7 March 1984). On those pages, the proof is presented that infinitely many models will reproduce any given field of motion. In addition, as just noted, radial stress will be nearly correct if motion is nearly correct. Hence, in the case at hand, infinitely many models will reproduce both radial stress and motion. ENCLOSED

22. Ref. 4, Sections 2.1, 3.2 and 4.3.

23. Shear-induced stress relief is also evident in laboratory stress-strain tests and in the Scooter field (Ref. 4, Section 4.2). At present, I view the former as inconclusive partly because only a few clear-cut tests have been made, but mostly because the relation between lab results and in-situ properties has yet to be firmly established for Yuma alluvium. As for Scooter, the sparseness of data and anomalies therein, mark it too as inconclusive.

24. Ref. 4, p. 42 and 43.

California Research & Technology, Inc.

11 April 1985
Ser: 5279

Dr. J. Trulio
Applied Theory, Inc.
930 S. La Brea Ave., Suite 2
Los Angeles, CA, 90036

Dear Jack,

I recently received a copy of your December 7th letter to Professor Belytschko referencing the discussion at the DNA/BMO meeting last December concerning the MP2 test. I fear you may have given Ted several erroneous impressions of the results, so I'm taking this opportunity to set the record straight concerning several of the 9 points you raise in your letter. In addition to the comments below, I am enclosing a copy of our MP2 final report. It includes plots of the reported velocity and stress waveforms and our calculated pre- and post-shot comparisons with these data.

As to the points in your letter:

1. ***Peak Radial Velocity vs Slant Range***: I agree with your assessment that almost all the preshot predictions (including CRT's) fall within a standard deviation of the data. I would only like to add that our post-shot calculations, in which we modified the fit to agree with WES's recommended post-shot curves, are also within the data spread. If your point is that peak velocity data from a spherically symmetric explosion are not a good discriminant of material properties, I certainly concur.

2. ***Rise Time to Peak Velocity***: I must take exception to your comments on rise times. First, I disagree with your presentation of the rise times as shown in Figure 1 (your Figure 2, from Figure 5 of your Reference 4). Your Figure shows rise times of about 12 ms at 9.5 m and 25-30 ms at 12.5 m. The data at those 2 ranges are shown in Figures 2 and 3. The main pulse at 9.5 m rises in less than 2 ms for each of the 5 gauges; the rise at 12.5 m is less than 5 ms. The very long rises you quote can only be justified if you include the very low level precursor. Such a precursor is probably not significant for the designs of current interest so including it in the rise time could result in very misleading conclusions in structure design.

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Rise times in the calculations are dependent on zone size as you suggest. In our reported calculations the zoning varied with range so that at 10 m zones were at least twice as large as those near the HE sphere. As shown in Figure 4, when run with constant zone size the rise to peak at the 9.5 m range is slightly steeper, as expected. The conclusion that code calculations should NOT be used to estimate rise times is certainly valid, but not new. Rarely, if ever, are the calculated rise times reported. NOTE: in the code/test comparison at the 9.5 m range, the calculated rise time of the main signal is LONGER than in the experiment, not shorter as you implied in Figure 1.

3. ***Peak Radial Stress vs Slant Range***: You argue that the stress gauges are probably less reliable than the accelerometers and I certainly agree. However, it does not follow that the stresses you derive from the accelerometer data are necessarily also more accurate. You do not show the error bounds of your analysis arising from either the errors in TOA's or waveforms. Since, if I understand the approach, your analysis uses the difference between 2 velocity waveforms to obtain the stress, won't the errors in each pulse compound the error in the final stress and/or strain time history? As I interpret your analysis (Reference 1, your Reference 4 again), you use an amplitude (A) and form (W) factor derived from the velocity data to generate your stress and strain results. It is interesting that the A-value you quote for the 5.2 m range is 108.5 mps, much higher than the data and almost exactly what we calculate. Whether you used the actual gage value or the 108.5 value, I suspect the peak stress at derived for 5.2 m has to be somewhat questionable.

   For what its worth, the peak stresses calculated pre- and post-shot (Figure 6) match the data inside the 14 m (~30 b level) range. Clearly the simple linear stick model breaks down in modeling the dynamics of the "elastic" toe which govern the farfield results.

4. ***Velocity Waveforms***: Although the gauges inside of 8 m are indeed inconsistent in both peak and decay, at the 9 m range (Figure 5), 4 of the 5 signals are quite consistent and the fifth isn't too far off. The calculations also show post-peak decay consistent with the shot. There is a difference in rise of the main wave between the calculation and the experiment, as seen in Figure 5, but the calculational rise is longer, just the opposite of your interpretation in point #2. Actually the rise of the pulse using uniform zoning (Figure 4) is a much better match to the data, although as stated in point #2, that is mostly coincidence.

5. ***Measured Radial-Stress Pulses:*** I don't have a copy of the Figures you Reference, but as I recall, your bounding pulses tended to have longer rise times and lower peaks than all of the stress data. I'm not sure though, what to conclude from this. Are you suggesting the gages are wrong and that we not make stress measurements? Seems to me, if we can't believe the stresses, we should eliminate those gauges in favor of more reliable ones? We are clearly doing the user community a grave disservice if we continue to report data which we don't believe (or know to be wrong). You also argue that the data are very insensitive to hoop stress. In light of the problems trying to measure radial stress, how can we hope to measure the hoop with any confidence, at least at this time. Using your analysis based on velocities to determine the quality of the stress measurements seems to be self-defeating. If we only accept a stress measurement if it agrees with the curve derived from the velocities, what additional information does the stress gage provide? Better to add more velocity gages.

6. ***Velocities, Pre-Shot and Predicted:*** You state the CRT velocity waveforms are smoother than those of ATI because of the linear unloading Q. Although the linear Q during loading is responsible for smoothing the waveforms in a hysteretic material, there is only a minimum additional effect when the linear Q is also used in unloading. The effect of various Q's is illustrated in the waveforms in Figures 7 and 8. Even the noisier waveform in the no linear Q case is probably acceptable. A properly chosen Q is necessary for both shock propagation and numerical stability. I would like to see a demonstration of a solution using reasonable values for the linear and quadratic Q constants that produce significant errors. I have never seen one. Otherwise, we should stop beating this dead horse.

   I really don't understand your second paragraph of 6. You seem to imply that it is not possible to make a prediction calculation of a shot if another similar shot had been fired first. Both PacTech and CRT used the WES recommendations to construct a material model and then used that model in a calculation of the MP2 event. While I certainly agree that we continue to modify our theoretical and experimental techniques based on experience, CRT explicitly set out to calculate MP2 with the current simplest possible fit to the WES recommended properties as a test of the state-of-the-art. I submit that these calculations are at least as much a prediction as empirical estimates based on previous shots and as such demonstrate the ability of the codes to predict the motions in very simple experiments, a necessary but not sufficient first step to calculating the more complicated tests of interest. Your notes 17 and 18 imply that the calculations were only consistent with MP2 and not predictions because "A theory can be consistent with existing measurements of a quantity, but it can only predict for a quantity what is not already known from measurement." Presumably then your empirical results were not predictions either, since they are also based on what is already measured. This sounds like the basis for a good philosophical (theological??) debate during a happy hour after some later meeting. Maybe Ted or Jim will supply the beer.

7. ***Radial Stresses, Pre-Shot and Predicted*:** You quote Reference 5 (yourself) and then seem to argue against the statements you made. I think I will let you resolve this argument among yourself. You also imply here and in 3 and 5 above that the radial stress measurements were both wrong and unnecessary since they are derivable from the velocity data. Similarly, I submit that hoop stress data, if it could be obtained, would also be accepted or discarded depending on whether it agreed with your analysis of the velocities. If that is the case why bother.

8. ***Volume Changes Due to Shear*:** The question of the volume change on unloading is certainly of interest, however, the difference between your analysis of the data and the code calculation does not appear to be as large as you suggest. I have sketched the calculated stress-strain and hoop vs radial strain curves for the 5 m point onto your Figure 9 (Figure 9). Although the calculation has some noise, both curves are in general agreement with your interpretation. The stress-strain curve deviates markedly from the uniax curves you show because; on loading, the material shocks up along the Rayleigh line, on unloading, the spherical divergence causes the radial strain to continue to increase (compress) while the calculated volumetric strain decreases. I would have to see error bounds to your analysis before deciding whether the differences in Figure 9 are significant, particularly in view of the uncertainties in the velocity records at the 5 m range. Also, Figures 8 and 9 of your Reference 4 show little or no post peak compression (Figure 10).

9. ***Significance of the MP2 Event*:** Here we appear to have reached diametrically opposite conclusions for primarily the same reasons. First, as stated in 8 above, I don't see the large difference between calculation and data that you do. Therefore, I still maintain that the calculations are in general and fundamental agreement with the MP2 test. Hence, it would be foolish to repeat

the test to obtain more data along strain paths in a test which "holds no interest per se" (your words). Rather I believe code predictions of MILLYARD and DRY CARES will be the true test of our current capability, in spite of the existence of the NSS, Pre-MILLYARD and MINI JADE events.

I hope the above comments help resolve some of the apparent discrepancies in our opinions and look forward to further stimulating discussions on material properties.

Sincerely,

Shel

Shel Schuster

SS:mw

cc:

J. Jones, DNA	W. Kitch, AFWL
C. McFarland, DNA	J. Thomas, AFWL
A. Schenker, BMO	E. Rinehart, CRT/A
J. Farrell, TRW	J. Thomsen, CRT/N
B. Lee, RDA	J. Bratton, ARA
J. Lewis, RDA	E. Jackson, WES
D. Simons, RDA	B. Pyatt, S-Cubed
T. Belytschko, NU	S. Peyton, S-Cubed
R. Allen, P-T	D. Burton, L-Cubed

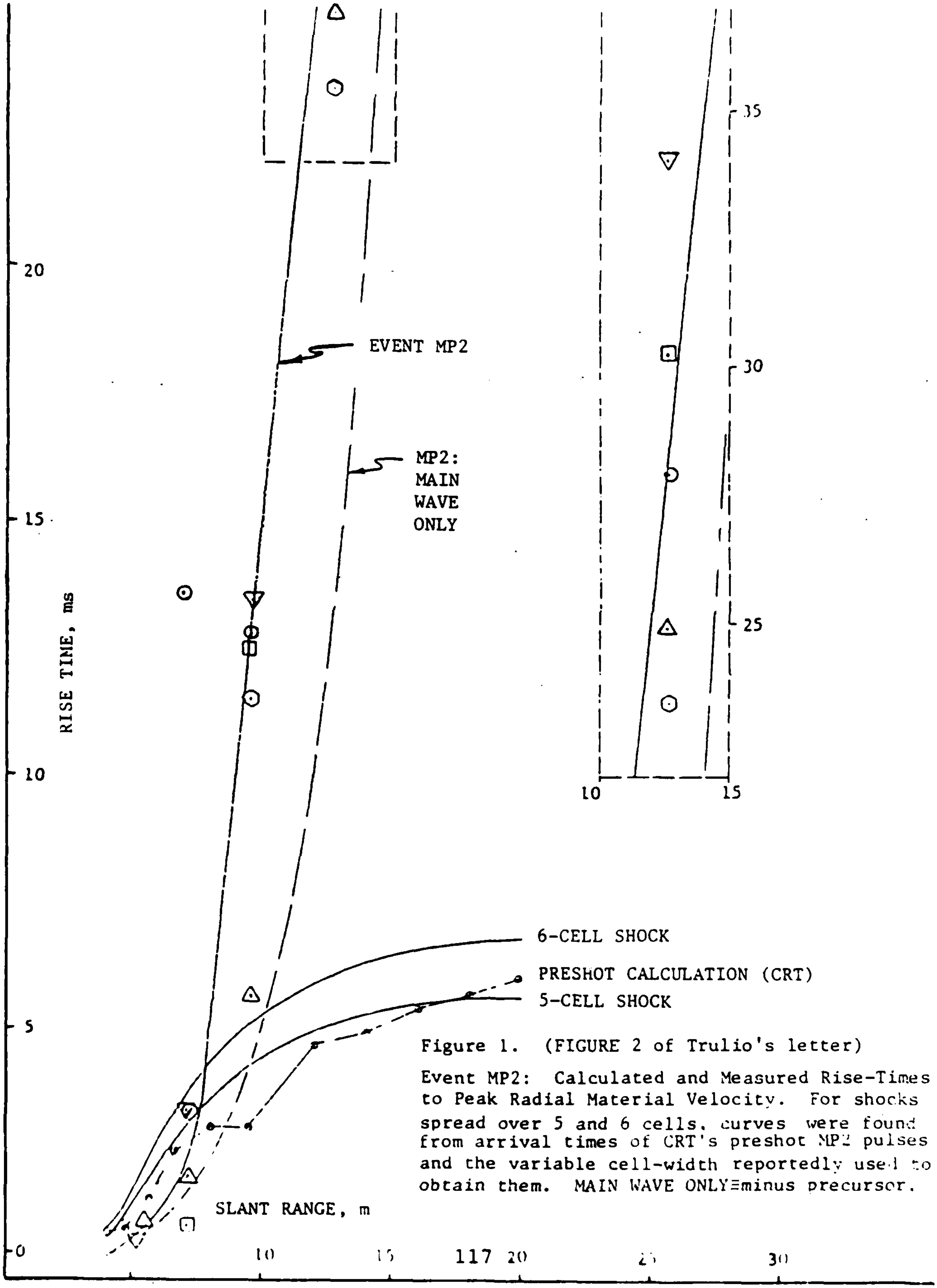


Figure 1. (FIGURE 2 of Trulio's letter)

Event MP2: Calculated and Measured Rise-Times to Peak Radial Material Velocity. For shocks spread over 5 and 6 cells, curves were found from arrival times of CRT's preshot MP2 pulses and the variable cell-width reportedly used to obtain them. MAIN WAVE ONLY≡minus precursor.

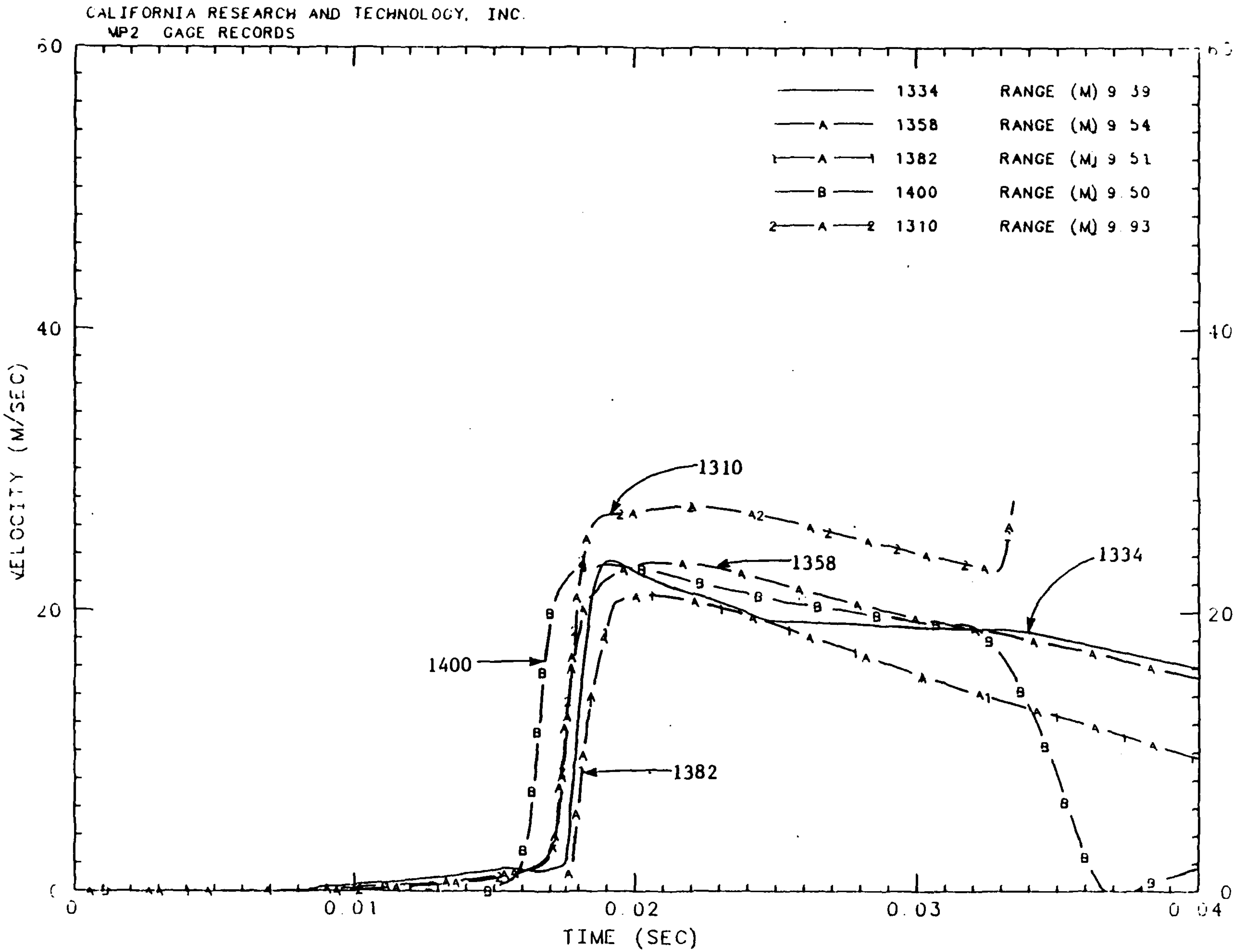


Figure 2. Radial velocity time histories from the 5 MP2 accelerometers approximately 9.5 m from the center of the NM. The peak stress is approximately 120 b at this range.

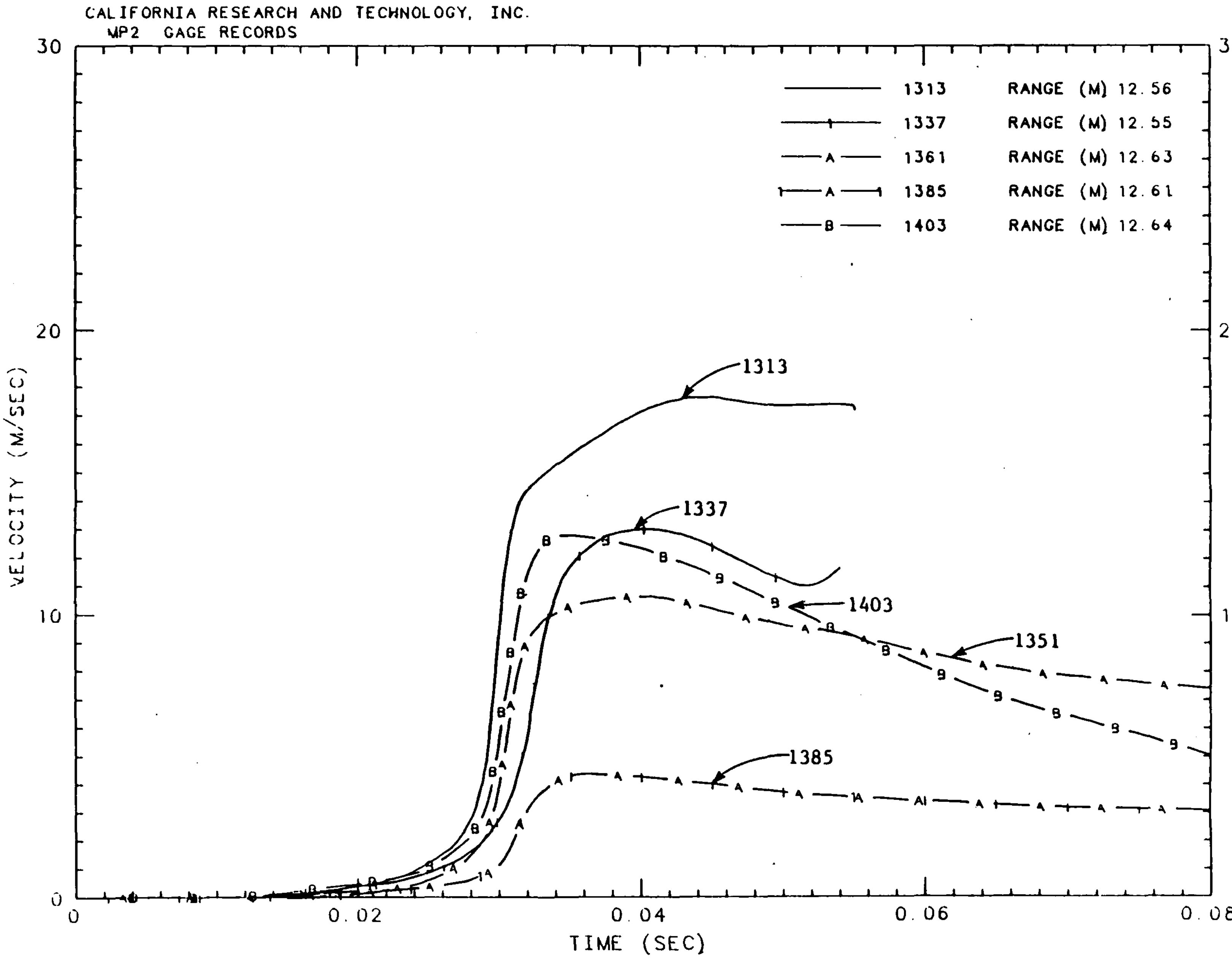


Figure 3. Radial velocity time histories from the 5 MP2 accelerometers approximately 12.6 m from the center of the NM. The peak stress is approximately 50 b at this range.

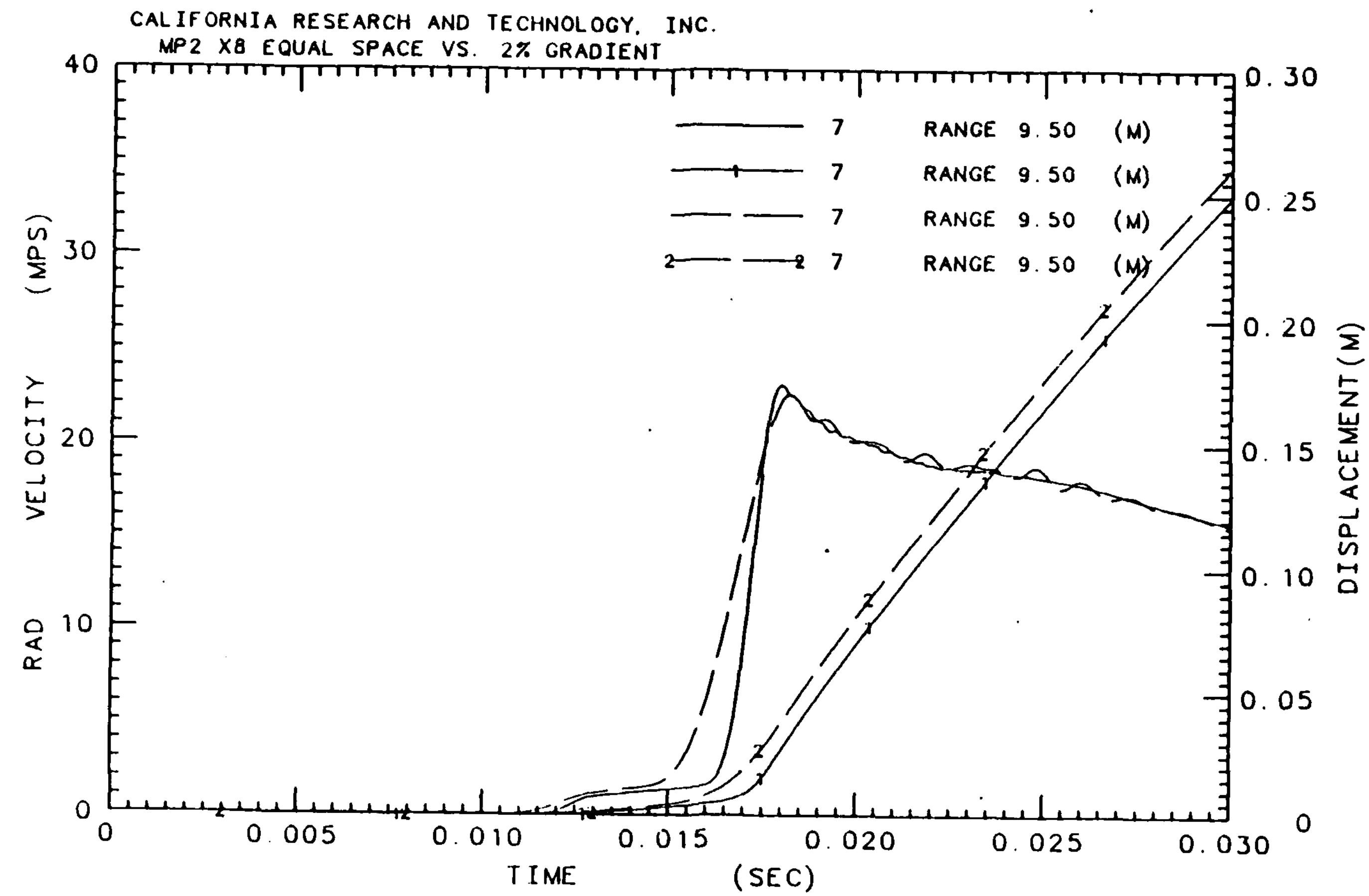


Figure 4. Effect of zoning on rise time at the 9.5 m range.

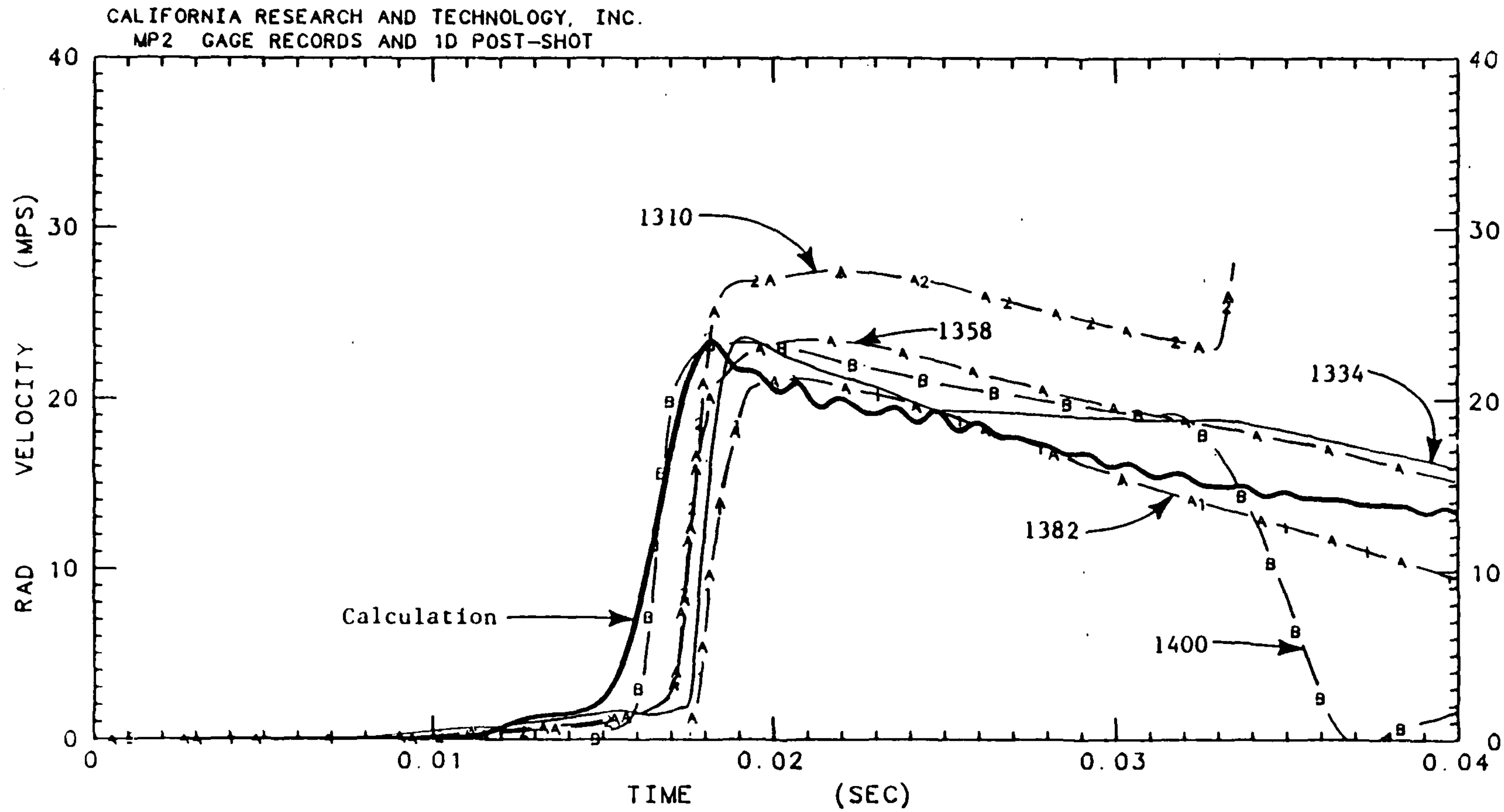


Figure 5. Comparison of the 1D post-shot calculated velocity time history at the 9.4 m range with the 5 MP2 records between 9.4 m and 9.9 m.

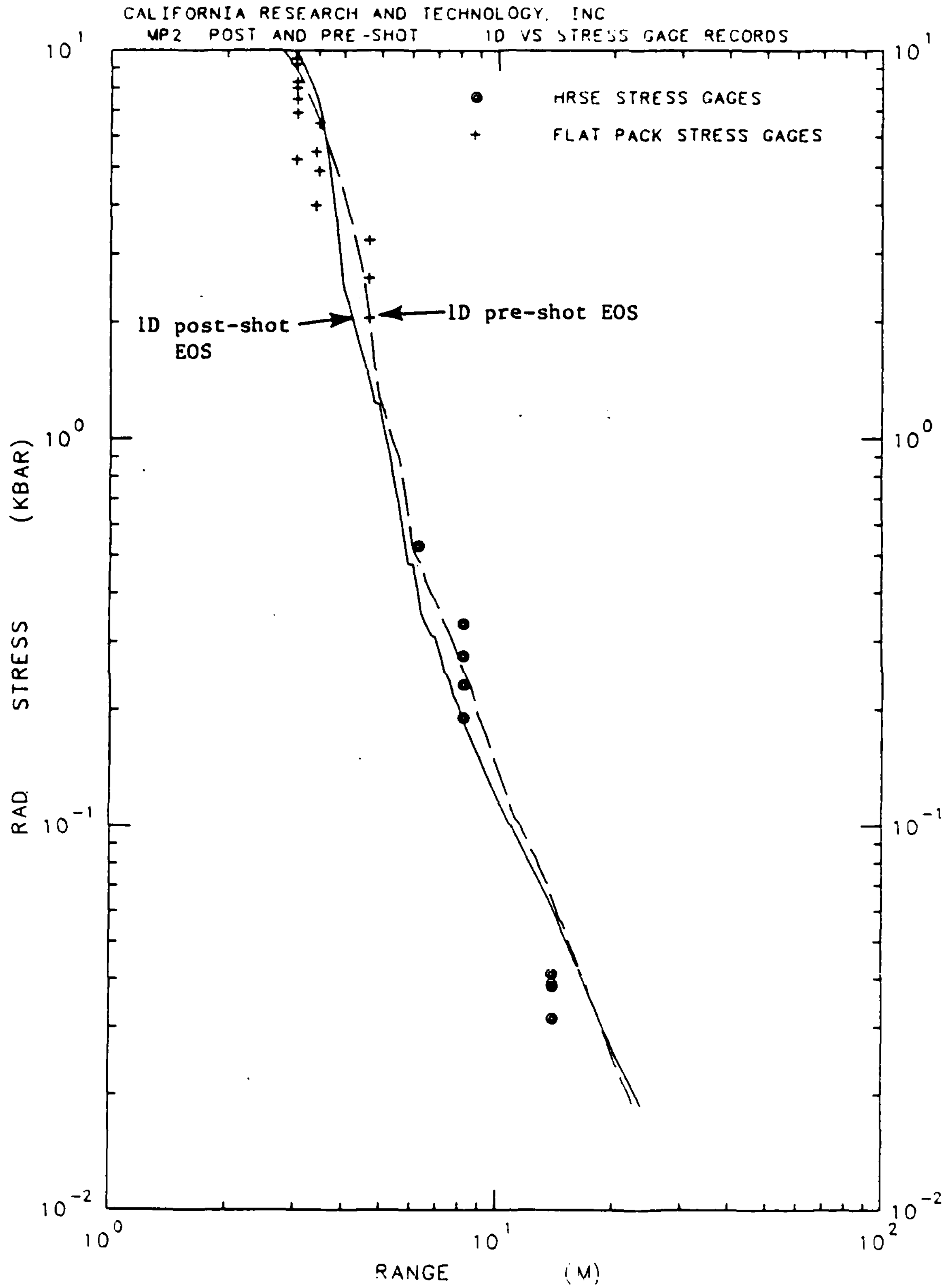


Figure 6. Comparison of the 1D pre- and post-shot calculated peak radial stresses with the MP2 data.

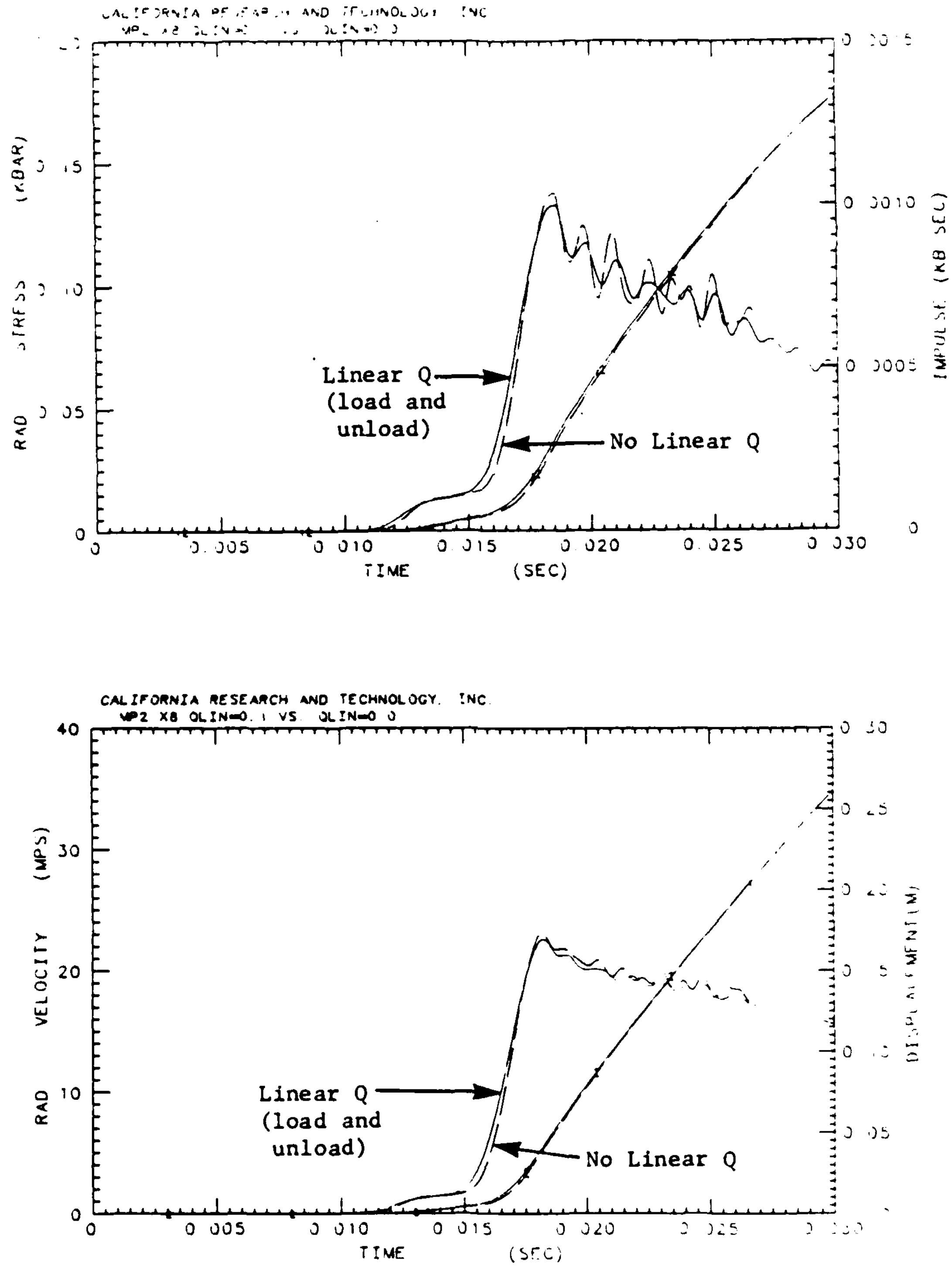
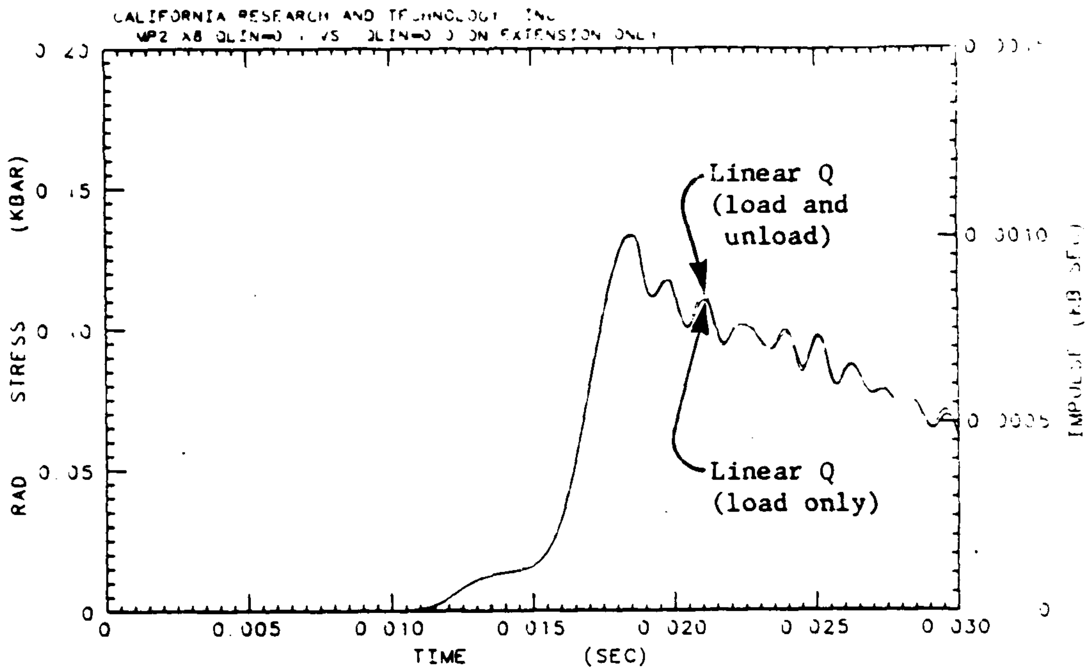


Figure 7. Effect on stress and velocity waveforms, at the 9.5 m Range, using full linear Q (loading and unloading) or not.



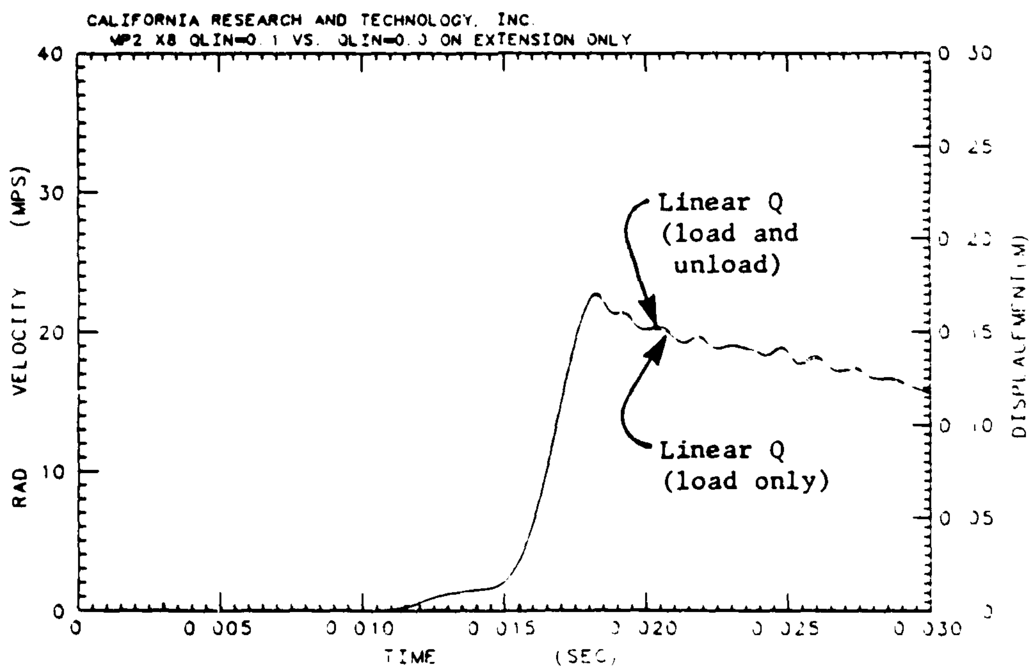
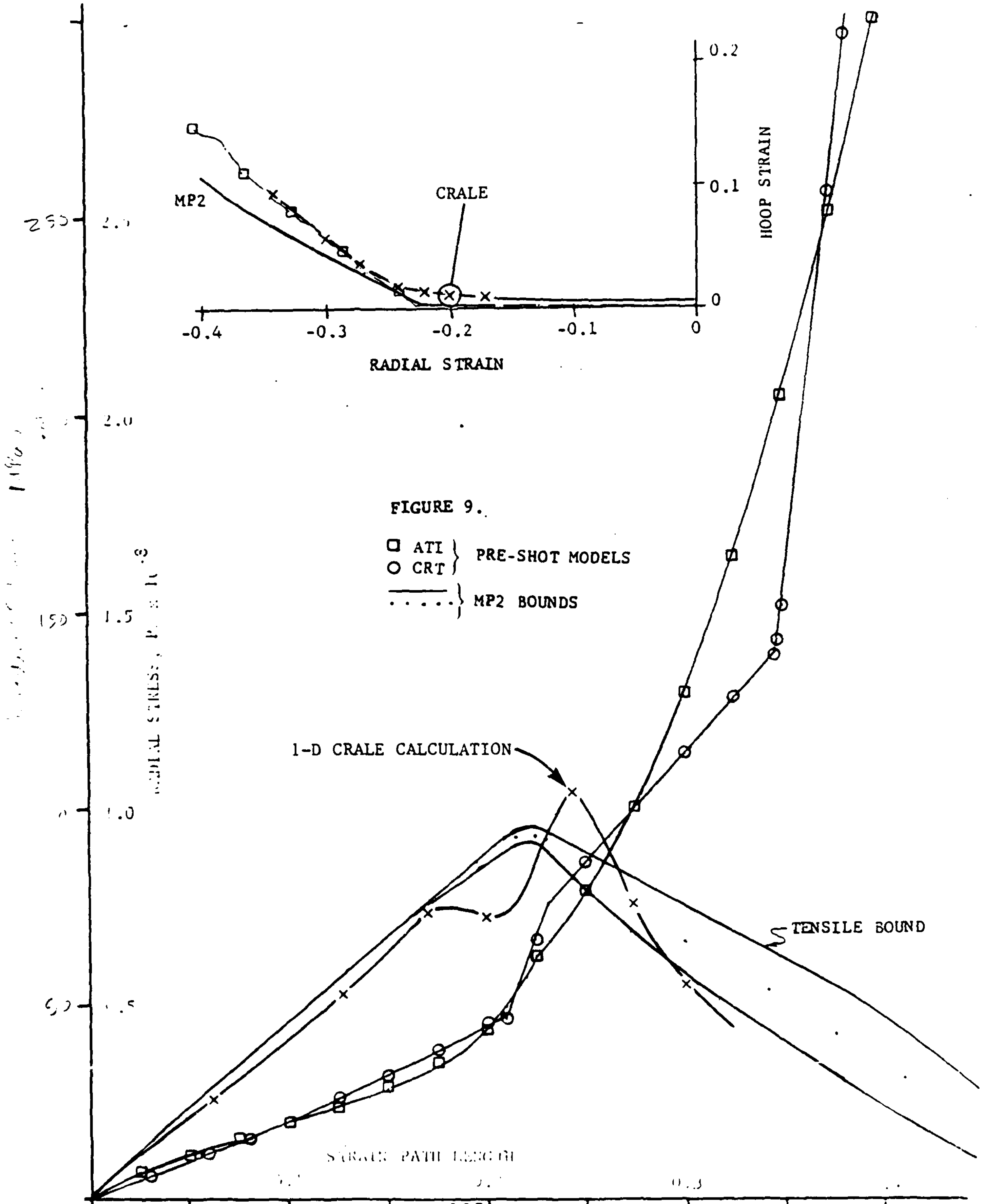


Figure 8. Effect on stress and velocity waveforms, at the 9.5 m Range, using the linear Q on loading only or both load and unload.


MP2
CRALE
0.2
0.1
0
HOOP STRAIN
-0.4
-0.3
-0.2
-0.1
0
RADIAL STRAIN
2.0
1.5
1.0
ATI
CRT
PRE-SHOT MODELS
MP2 BOUNDS
1-D CRALE CALCULATION
TENSILE BOUND
FIGURE 9.

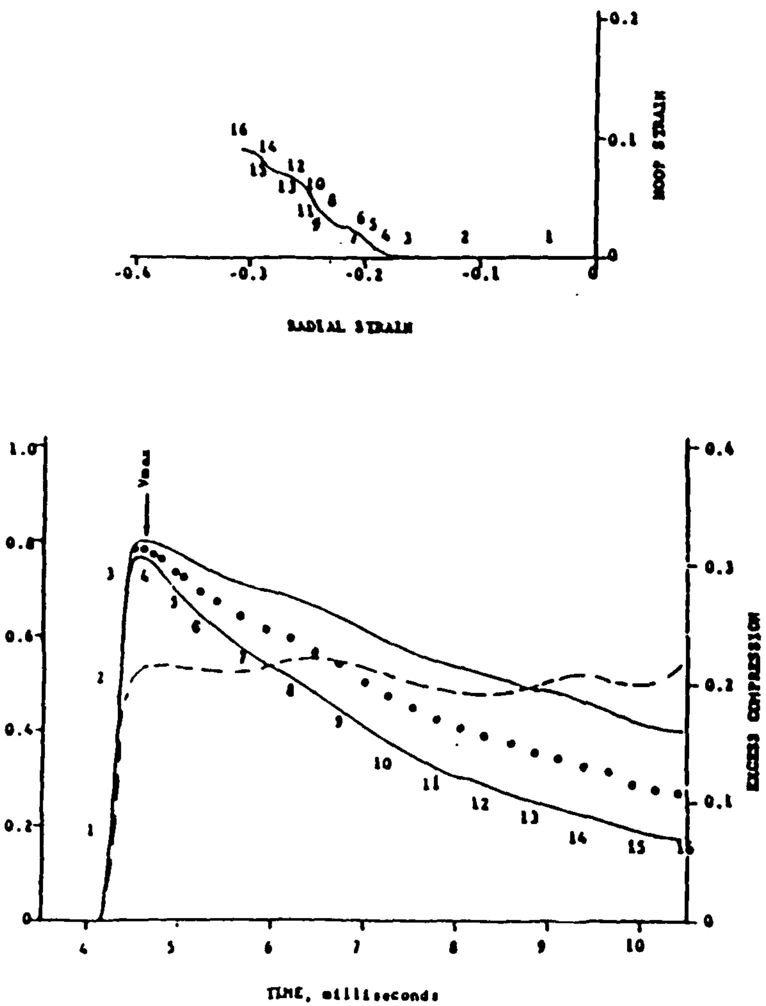


Figure 8. Strain Path and Stress Bounds for Event MP2 at a Slant Range of 5.22 Meters. Excess compression (density divided by initial density, minus 1; dashed curve) is also shown vs. time. Except for the use of a quadratic least-squares fit to measured peak velocities, rather than a linear fit, the curves were obtained exactly as in Fig. 3. The format is that of Fig. 2.

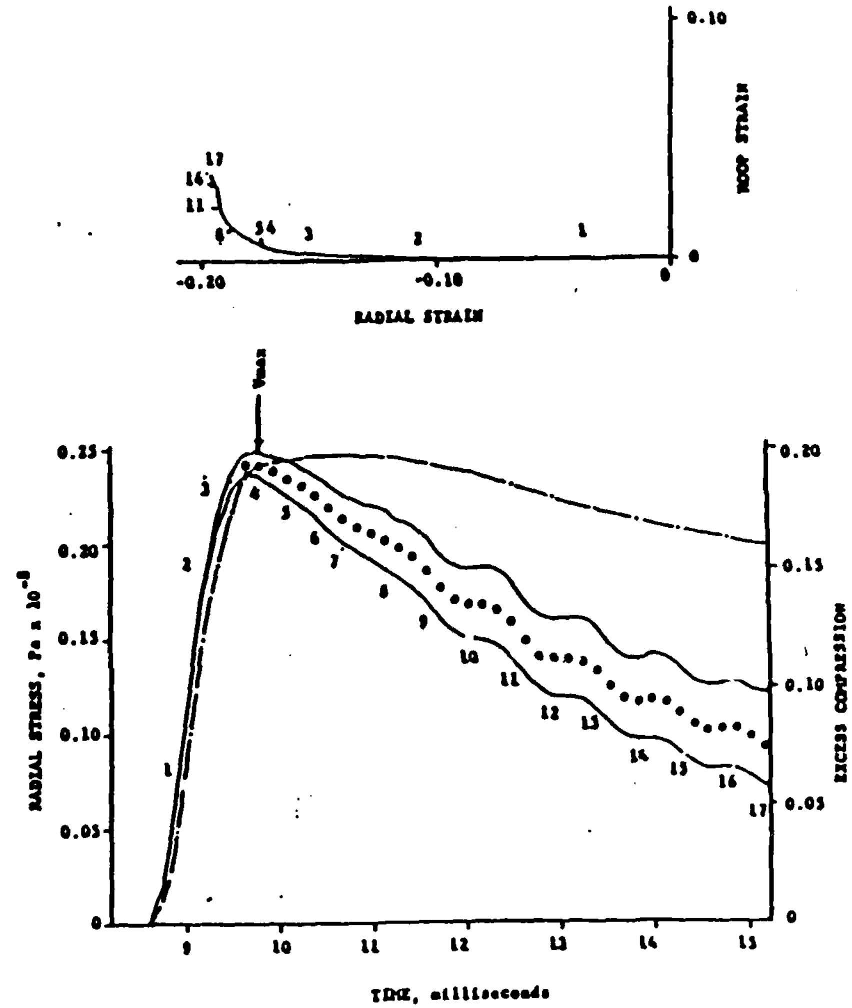


Figure 9. Strain Path and Stress Bounds for Event MP2 at a Slant Range of 7.06 Meters. Excess compression (density divided by initial density, minus 1; dashed curve) is also shown vs. time. The waveforms used in generating the curves were those of Pulses 2a and 3 (Fig. 1). The format is that of Fig. 6.

Figure 10

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